

SPECTRAL REFLECTANCE ESTIMATES OF
LIGHT INTERCEPTION AND PHOTOCHEMICAL EFFICIENCY IN
WHEAT UNDER DIFFERENT NITROGEN REGIMES

by

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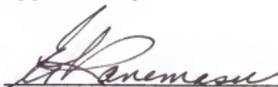

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INTRODUCTION

"The historical development of the study of plant growth affords a good example of how much more difficult it is to carry out quantitative than qualitative studies."

(G.C.Evans in The Quantatative Analysis of Plant Growth, Cambridge 1972.)

Genetic variability interacting with fluctuating environmental conditions make quantification of plant growth a complex and difficult process. Remote sensing has the potential of characterizing and quantifying plant and environment interaction over a large sample area non-destructively and economically. To interpret effectively remotely sensed data, an understanding is needed of the physical and physiological basis for the uniquely characteristic energy pattern reflected and transmitted from the vegetation to the sensor.

Leaf and Canopy Reflectance

Plant growth and productivity are dependent upon energy acquired from the sun. Plants differentially absorb, reflect, and transmit solar radiation at selective wavelengths. By monitoring and quantifying the reflected and transmitted energy from several discrete wavelength bands, a measure of a crop's condition can be obtained.

A typical reflectance spectrum of a plant leaf is presented in Fig. 1. Reflectance of plant leaves is relatively low in the visible portion of the spectrum (0.40 to 0.70 μm) with a small peak at approximately 0.55 μm which accounts for the green color of plants as perceived by the human eye. Reflectance increases sharply in the near-infrared region (0.70 to 1.00 μm).

The high reflectance of leaves in the near-infrared region has been attributed to their internal structure. Willstatter and Stoll (1913), as reported by Gates et al. (1965), proposed that multiple scattering occurred at the cell wall-air interface of spongy mesophyll tissue when light passing through an area of low refractive index (air) strikes an area of higher refractive index (cell wall) at an angle of incidence greater than the critical angle for reflection. Knipling (1970) hypothesized that this scattering is more likely to occur in the region of the palisade cells where many small air cavities and large areas of exposed cell wall are found. He further stated that there would be a physiological advantage to the leaf for scattering to take place primarily in the palisade region due to the region's high concentrations of photosynthetic pigments. Gates et al. (1965) suggested that scattering within the leaf can also be caused by structures of the dimension of a wavelength of light. Gausman (1977) confirmed this, showing that stomata,

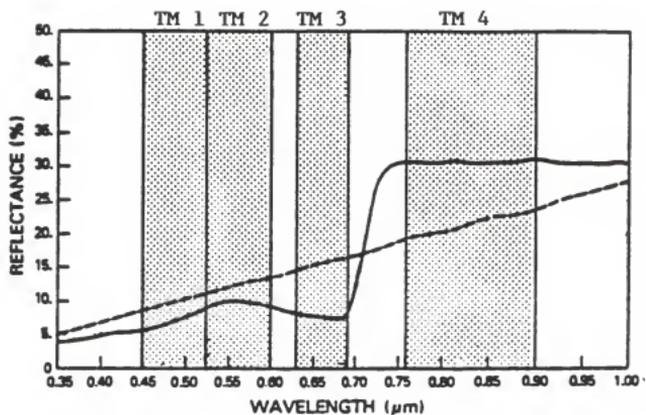


Fig. 1. Reflectance of radiation by a typical green leaf (solid line) and dry soil (dashed lined) with the Thematic Mapper bands of the Exotech 100BX-T denoted by the shaded bars; adapted from Tucker et al. (1979).

nuclei, and other cell organelles contributed to the reflectance of light in the near-infrared region using infrared photography. The Willstatter-Stoll theory would suggest that the collapse of the spongy mesophyll region of the leaf (as might occur in a water stressed leaf) would cause a decrease in near-infrared reflectance. Sinclair et al. (1973), working with dehydrated leaf tissue, found that near-infrared reflectance increased as the moisture content of the leaves decreased. They showed that this increase was due to scattering of the radiation by the cell walls and proposed a modification of the Willstatter-Stoll theory to account for this phenomenon. Gates et al. (1965) showed that photosynthetic pigments are highly transparent in the near-infrared region, and highly absorptive in the visible region of the spectrum. It is the low reflectance and transmittance of visible radiation attributable to the high absorption of photosynthetic pigments and the high transmittance and reflectance of near-infrared radiation due to the leaf internal structure which is the basis for much of radiometric remote sensing of vegetation.

Physiological factors that affect leaf reflectance include plant maturity, water content, pigment concentration, pubescence, waxiness, and environmental stresses, such as soil salinity, toxicities, and nutrient deficiencies (Gausman et al., 1978; Lapitan, 1986). The

individual leaf, at maturity, will present an integration of the effects of varying environmental factors for the period up to that time.

In laboratory studies relating nutrient deficiencies to leaf reflectance, Al-Abbas et al. (1974) found that leaves from S, Mg, K, and N deficient maize (Zea mays L.) plants had increased reflectance in the visible wavelength and decreased reflectance in the near-infrared wavelengths. These differences were attributed to a reduction of leaf chlorophyll content, cell size, and cell number induced by the nutrient deficiencies. In contrast, Thomas and Oerter (1972) found an inverse relationship between both visible and near-infrared leaf reflectance and the nitrogen (N) content of sweet pepper (Capsicum annum L.) leaves.

It is not possible to interpret the reflectance of a plant canopy only on the basis of individual leaf reflectance. There are quantitative and qualitative differences in the two spectra due to variations in illumination angle, look angle, leaf area index (LAI), leaf orientation, and nonfoliage background surfaces, such as soil (Knipling, 1970).

Tucker et al. (1979) found that canopy reflectance data of maize and soybeans [Glycine max (L.) Merr.] were scattered erratically by varying solar intensities, sun angles, and atmospheric conditions at the different data

collection times. In order to partially compensate for this variability they suggested that the ratio of canopy reflectance from near-infrared and red (NIR/R ratio) wavelength bands or the ratio of the difference and the sum of these wavebands $(NIR-R)/(NIR+R)$, (Normalized Difference), were effective transformations which could be used as indices of vegetative growth.

Field studies (Walburg et al., 1981; Hinzman et al., 1986) relating nitrogen (N) deficiencies to reflectance have shown that different N treatments can be distinguished by reflectance. These researchers reported that with increasing N application canopy reflectance decreased in the visible and middle infrared wavelength regions and increased in the near-infrared wavelength region. Walburg (1981) attributed these changes to differences in LAI, percent soil cover, plant biomass, leaf structure, and composition including pigment concentration. Stanhill et al. (1972) concluded that spectral response of N deficient wheat canopies was primarily related to differences in total phytomass and only secondarily to leaf optical properties and canopy geometry.

Spectral Estimates of Plant Growth

Monteith (1972) showed that phytomass production could be conceptually related to the time integral of

plant canopy absorbed photosynthetically active radiation (APAR). Mathematically this relationship can be written as:

$$PM = \int_{t_0}^{t_n} E_s E_c E_i S dt \quad [1]$$

where PM = production of dry phytomass ($g m^{-2}$)

E_s = fraction of photosynthetically active radiation (PAR) in whole spectrum radiation

E_c = the efficiency of conversion of solar energy (photochemical efficiency) to dry matter ($g MJ^{-1}$)

E_i = interception efficiency

S = solar radiation ($MJ m^{-2}$)

t = time period

In Monteith's notation, APAR is equal to the product of E_s , E_i , and S .

Monteith (1972) showed that the fraction of whole spectrum radiation absorbed by green leaves (E_s) is made up of two components. The first component is the fraction of solar radiation which is photosynthetically active (PAR). PAR is dependent upon the water vapor and dust content of the atmosphere. Szeicz (1970) found this to vary only slightly from 0.48 in the spring to 0.51 in the winter. The second component of E_s is the fraction of PAR absorbed by leaves, and is dependent upon factors such as

pigment concentration per unit leaf area. Monteith assumed an average figure of 0.85 for the second component and 0.425 for Es ($0.50 * 0.85 = 0.425$) overall.

Charles-Edwards (1982) estimated the upper limit of Ec to be 6.4 g of dry matter per MJ of APAR, and cited research in which estimates of 1.3 to 4.2 g MJ⁻¹ were found in different crops. Studies of the response of Ec to environmental stress are inconclusive. In various laboratory and growth chamber studies, researchers have found strong correlations between N supply and net photosynthesis. Bolton and Brown (1980) found that net photosynthesis increased linearly with N supplied in experiments on three grass species. Plants grown with optimum nutrition were transferred from the field or a greenhouse to flasks containing Hoagland's solution. N was supplied in the form of NH₄NO₃ at 1, 5, 50, and 200 mg l⁻¹. Some tillers of the high N treatments were broken off in order to maintain similar plant sizes among N treatments. Using similar procedures Nevins and Loomis (1970) and Robson and Deacon (1978) working with sugar beets (Beta vulgaris L.) and ryegrass (Lolium perenne L.), respectively, found that net photosynthesis was positively correlated with N supply.

In a field experiment relating effects of temperature and N supply to post floral growth of wheat, Vos (1981) found that effects of N on photosynthate production were

primarily brought about by effects on size and duration of the green leaf area. Gallagher and Biscoe (1978), in studies of wheat, found that Ec based upon above- and below-ground phytomass production varied from 2.8 to 3.1 g MJ⁻¹ for fertilized and unfertilized treatments, respectively. Legg et al. (1979) found that in barley (Hordeum vulgare) grown under water stress less than 15% of the reduction in phytomass production could be attributed to decreases in Ec, whereas 85% of the reduction was due to a decrease in the intercepted radiation. Using leaf area index (LAI) to estimate light interception, Green et al. (1985) found that drought reduced the seasonal Ec in two cultivars of Vicia faba by 37 and 29 percent. In the absence of moisture stress, they found Ec to be constant throughout the season with a mean value of 3.21 g MJ⁻¹. In an experiment examining the effects of water stress on sunflower (Helianthus annuus L.), Connor et al. (1985) found that Ec decreased during post-anthesis growth, with water-stressed treatments having greater decreases than unstressed treatments. Charles-Edwards (1982) suggested that Ec was temperature dependent, and increased with increasing temperature. In contrast, Monteith and Elston (1983) suggest that Ec may be insensitive to temperature, water stress, and nitrogen supply during vegetative growth, and therefore, relatively constant.

Monteith (1972) concluded that the interception efficiency (Ei), which he defined as the ratio of actual gross photosynthesis to the maximum rate estimated for a stand of identical plants with enough leaves to intercept all the incident light, is a major discriminant of dry matter production, accounting for differences in productivity due to climate and management.

Various studies have shown that Ei can be estimated using remotely sensed multispectral data (Daughtry et al., 1983; Hatfield et al., 1983). Wiegand et al. (1986) suggested that a vegetation index may be a more accurate monitor of photosynthetic capacity of standing canopies than leaf area index (LAI) especially during crop senescence because spectral indices can respond to non-leaf photosynthetically active tissues such as heads and leaf sheaths of cereals.

Lapitan (1986) needed different equations to estimate Ei from spectral indices for wheat (Triticum aestivum L.) grown in various row structures. He found that Ei varied linearly with the normalized difference (ND) and exponentially with the near-infrared/red (NIR/R) ratio. In an experiment with irrigated wheat and multiple planting dates, Asrar et al. (1984, 1985) estimated Ei values from ND. A canopy temperature-based stress indicator and the daily Ei values were then used to

estimate above-ground phytomass production. The intent of the present research is to determine if similar procedures can be applied to crops grown under different nutrient regimes, and to examine the photochemical efficiency of dry matter production under these regimes.

MATERIALS AND METHODS

Design of the Experiment

The experiment was conducted during the 1984-1985 growing season at the Evapotranspiration Research site located 6 km south of Manhattan, Kansas (39°09' N and 96°37' W). The plots were on a leveled Muir silt loam soil (fine-silty, mixed, mesic Cumulic Haplustoll). Wheat was grown on the same site during the 1983-84 season. The seedbed was disced, chiseled, and harrowed before planting.

Twenty-four treatment combinations, including three levels of irrigation, four levels of nitrogen fertilization, and two cultivars, were replicated four times in a split-split plot design. Within each irrigation level (whole plot) there were four blocks (replications) of a factorial experiment with nitrogen as the subplot and cultivar as the sub subplot. Plots were one drill-width wide (3 m) and 15 m long. Borders were 6 m wide and alleys between replications and between water levels were 3 m wide.

Soil samples were collected for nutrient analysis at four depths (15, 30, 45, and 60 cm) before and after the growing season. Thirty-one kg/ha of P_2O_5 and ten kg/ha of liquid nitrogen were applied to all plots 20 September

1984. To obtain desired nutrient levels, nitrogen in the form of ammonium nitrate pellets was applied by hand 24 October 1984 at the rate of 35, 80, and 190 kg/ha in treatments N45, N90, and N200, respectively.

Two cultivars of winter wheat (Triticum aestivum L. cv. 'Newton' and 'Colt') were planted in north-south row orientation on 22 September 1984. Planting was at a depth of approximately 5 cm and row spacing of 18 cm.

Agronomic Measurements

Plant population counts (Appendix, Table 1) were conducted on a 1 m² area in each of the treatments 45 days after planting (Hauns growth stage 1.8). Three plants in each treatment were tagged and growth stage data were assessed and recorded at weekly intervals (Appendix, Table 2). Lodging was assessed and recorded (Appendix, Table 3) on a percentile basis.

Neutron probe tubes were installed 23 October 1984. A Troxler neutron probe (Model #3221, Research Triangle Park, NC) was used for soil moisture measurements, which were taken (Appendix, Tables 4 and 5; Fig. 1-3) twice in the fall and once every two weeks in the spring starting 27 March 1985. The measurements were made with the probe detector centered at depths of 30, 45, 60, 90, 120, 150, 180, 210, and 240 cm. Gravimetric procedures were used to determine moisture content in the surface 15 cm.

Available moisture for irrigation scheduling was determined using field capacity and permanent wilting point values which were developed for the site over a period of eight years. The plots were bermed and then surface irrigated using gated pipe on 25 April 1985; 4 cm of water was applied to W2 and 7 cm to W3. Water level 1 (W1) comprised the non-irrigated block.

Estimates of stem, head, green leaf, dead leaf, and total above-ground phytomass were made (Appendix, Tables 6 and 7) from samples of 12 plants per treatment from two replications collected once in the fall and six times in the spring between 15 March and physiological maturity (15 June). Representative subsamples of four plants were selected for measurement of leaf area, leaf number, tiller number, and plant height. Leaf area was determined using an optical planimeter (LI-COR Model 3100, Lincoln, NE).

Plots were harvested for grain yield (Appendix, Tables 8 and 9) 1 July. A 2.16 m² area (4 rows * 1 m * 3 sub-samples) was harvested from each plot. Total above-ground phytomass was measured at the site. Grain was weighed and moisture content was determined using a digital moisture meter (Burrows model #700, Evanston, Illinois). A sample of the straw was weighed and placed in ovens for drying, in order to determine moisture content and dry phytomass.

Spectral Measurements

Canopy spectral reflectance data were collected using an Exotech 100-BX 4-band radiometer (Gaithersburg, MA). The radiometer was configured with 15° field of view lens and thematic mapper (TM) bandpass filters. This configuration includes three wavebands in the visible (TM1=0.45-0.52, TM2=0.52-0.60, TM3=0.63-0.69 μm) and one in the near infrared region (TM4=0.76-0.90 μm) of the electromagnetic spectrum. The radiometer was mounted in the nadir viewing position on a handheld boom 2.8 m above the soil surface. Five measurements were taken from each plot with observations from all 24 treatment combinations requiring 20-22 minutes. Data were collected from the middle two replications, with collection from each replication being preceded and followed by measurements over a BaSO_4 (Lambertian) reference panel. Canopy reflectance values were determined by dividing the canopy radiance by the reference panel radiance. The data were logged and stored in a portable data acquisition system (Omnidata Polycorder Model 516A, Logan, UT) in the field. A score was given for the quality of atmospheric conditions prevalent at the time of collection. Solar radiation, air temperature, wind speed, and rainfall were monitored at a weather station located 100 meters from the experimental site.

Data Analysis

Near infrared (TM4=0.76-0.90 μm) and red (TM3=0.63-0.69 μm) canopy reflectance values were used to compute vegetation indices.

Normalized difference (ND) was calculated as:

$$ND = \frac{TM4 - TM3}{TM4 + TM3} \quad [2]$$

Near-infrared/red ratio (NIR/R) was calculated as:

$$NIR/RED = \frac{TM4}{TM3} \quad [3]$$

Seasonal trends of the indices were determined and a cubic spline procedure (Spath, 1974) was used to calculate daily values which were used in the estimations of interception efficiency (Ei) of the wheat canopy. Ei was computed using [4] and [5], which were developed for wheat grown at 18 cm row spacing by Lapitan (1986).

$$Ei = -0.0248 + 1.0935 * ND \quad [4]$$

$$Ei = .9713 * (1 - 1.5468 * \exp(-0.2897 * NIR/R)) \quad [5]$$

RESULTS AND DISCUSSION

Seasonal Patterns of Canopy and Spectral Development

There were no extended periods without precipitation during the 1985 growing season (Appendix, Fig. 1). Two days after the only irrigation of the season the experimental site received 10 cm of rainfall. Analysis of the periodic plant sampling data revealed that differences between treatments were primarily due to nitrogen (N) (Appendix, Table 6). There were no significant differences in treatment interactions between N, water, and cultivar. Leaf number and head weight were significantly greater in the Newton cultivar, but consistent patterns of effects due to cultivar could not be found in any of the other parameters. The following analysis, therefore, focused on nitrogen effects.

The seasonal response of leaf area index (LAI) to N fertilization is presented in Fig. 2; a cubic spline procedure (Spath, 1974) was used to fit a smooth curve to the observed data. The maximum LAI and leaf area duration were highly responsive to N supply. These responses provided distinctive canopies for canopy reflectance measurements. High levels of N application (200 and 90 kg ha⁻¹) resulted in a more rapid rate of leaf expansion during the period from double ridge to boot.

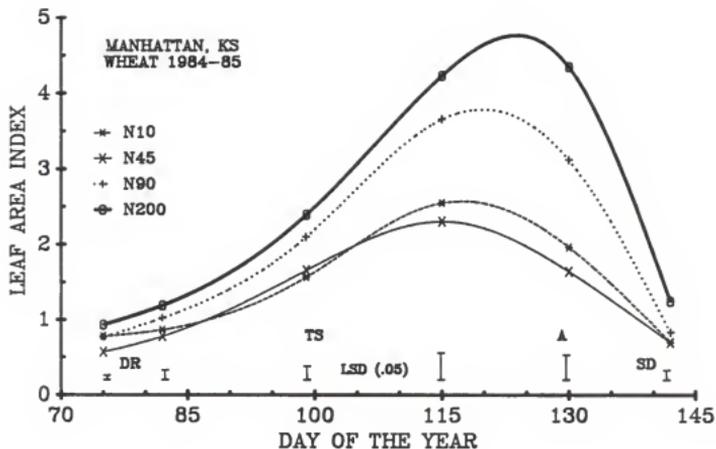


Fig. 2. Seasonal changes in leaf area indices of winter wheat. Growth stages are indicated by DR, Double Ridge; TS, Terminal Spikelet; A, Anthesis; and SD, Soft Dough. Data are means of 12 observations, with each observation being a mean of 4 subsamples.

Plants in the high N treatments also maintained leaf area for a longer period.

Spectral responses and LAI of the wheat canopies appeared to follow the same pattern. The effects of varying N fertilization on the spectral indices ND and NIR/R ratio were seen throughout the season (Fig. 3). Although both indices were effective in distinguishing the greater LAI and ground cover of the high N canopies, NIR/R ratio appeared more effective than ND in representing the large differences in the canopies during the period of peak LAI (day 115 to 130). This is due to the asymptotic pattern of ND at peak LAI (Asrar et al., 1984). Below a LAI of 1.0, normalized difference appeared more effective in discriminating among the crop canopies.

Canopy reflectance did not present the same pattern as LAI in the N200 treatment. The peak canopy reflectance of the N200 treatment was earlier than peak canopy reflectance of lower N treatments, in contrast to the LAI pattern in which N200 reached peak LAI later than the lower N treatments. This discrepancy could be partially attributed to lodging (Appendix, Table 3). Lodging exposed senescent plant material resulting in higher red reflectance and reduced values for the vegetation indices.

Interception efficiency (E_i) was estimated using [3] and [4] developed by Lapitan (1986). These estimates are

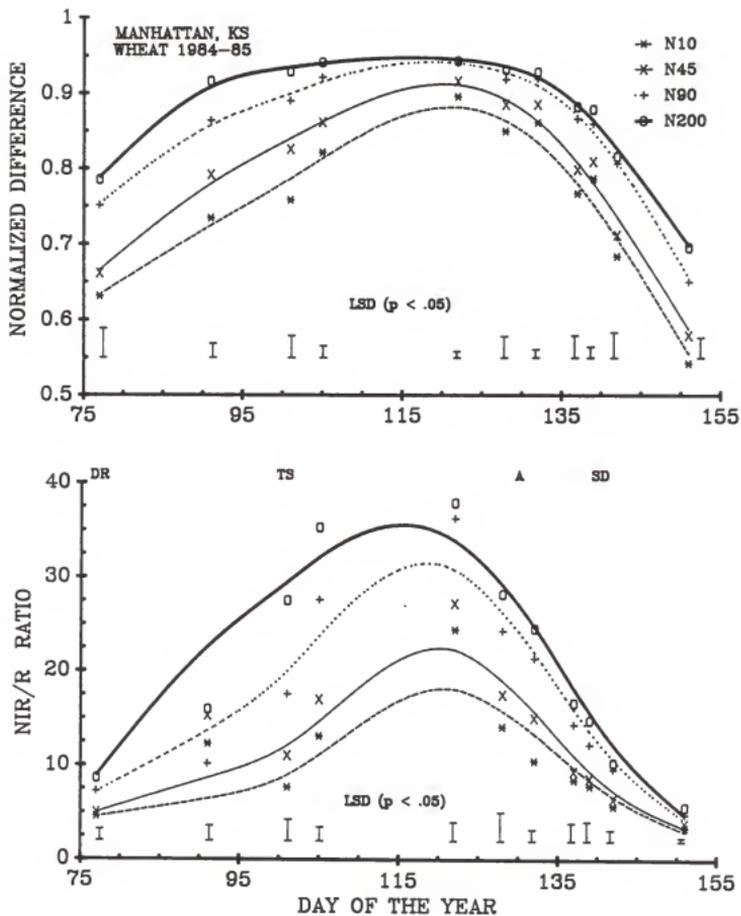


Fig. 3. Seasonal changes in normalized difference and near infrared/red ratio. Growth stages are indicated by: DR, Double Ridge; TS, Terminal Spikelet; A, Anthesis; and SD, Soft Dough. Data are means of 12 observations with each observation being a mean of 5 measurements.

presented in Fig. 4. The relationship between ND and E_i is linear and any treatment effects on canopy reflectance will be represented in ND-based estimates of E_i .

Due to the exponential relationship between E_i and NIR/R ratio, estimates of E_i from NIR/R were asymptotic once LAI reached a value of two. Therefore, the effectiveness of NIR/R ratio in distinguishing canopy differences at peak LAI periods was not carried over to the estimates of E_i derived from NIR/R ratio. We chose not to use NIR/R ratio in any of the following analyses.

Prediction of Phytomass Production

The estimates of E_i derived from ND were used in [1] for predictions of above-ground phytomass production. Gallagher and Biscoe (1978) found that E_c based upon above- and below-ground phytomass production of barley and spring and winter wheats over multiple sites, seasons, and cultivars was relatively constant at 3 g MJ^{-1} for the period from seedling emergence until the start of head emergence. Monteith (1981) suggested 2.9 g MJ^{-1} as an appropriate general value for E_c , as this analysis was based upon above-ground phytomass measurements this lower value was used in the calculations. The fraction of PAR in whole spectrum radiation (E_s) was assumed to be 0.425. Daily values of solar radiation were obtained from measurements taken at the experimental site weather

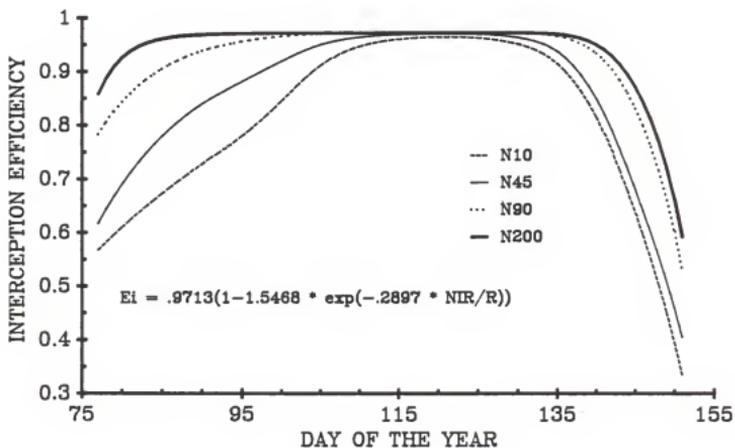
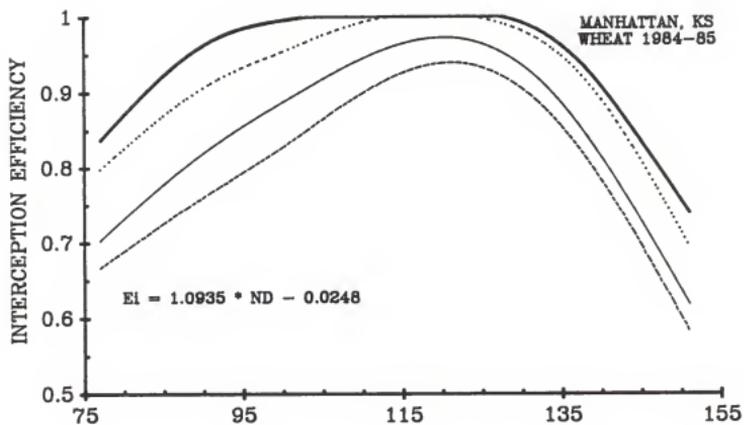


Fig. 4. Seasonal pattern of estimated interception efficiency (E_i) using ND (a) and NIR/R ratio (b).

station. The regression model for phytomass production and predicted phytomass production (Fig. 5) are given in Table 1.

Table 1. Regression coefficients and 95% confidence limits for the linear model between predicted and measured above ground phytomass production using ND in the estimation of E_i .

INTERCEPT $g\ m^{-2}$	SLOPE $g\ m^{-2}/g\ m^{-2}$	R-SQUARE
-124.59 ± 97.62	1.052 ± 0.092	0.97

The high coefficient of determination (R^2) indicates a strong correlation between measured and predicted phytomass values using ND to estimate E_i . The slope is not significantly different from one, but the intercept is less than zero. The significant intercept is due to overestimations of phytomass for the early sampling dates. In computations, a fixed value for E_c was used throughout the season. However, E_c may change due to environmental factors and their interactions with plant growth. Such a possibility will be examined in the next section.

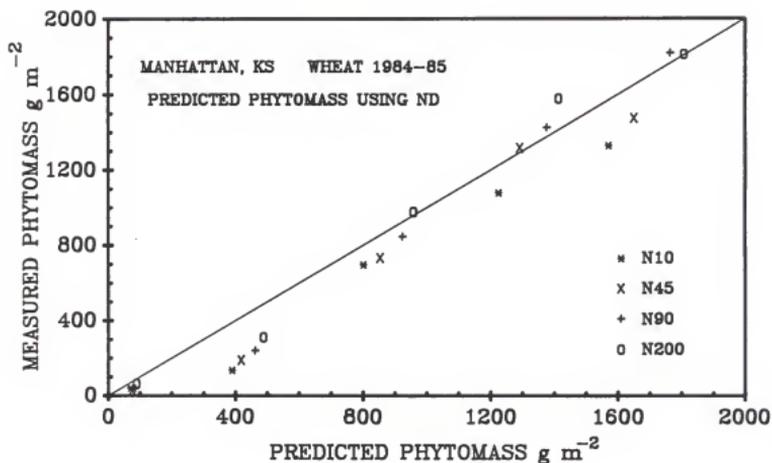


Fig. 5. The relationship between measured and predicted phytomass production using ND to estimate interception efficiency.

Photochemical Efficiency of Conversion

E_c can be estimated by the slope of the line describing the relationship between cumulative phytomass production (PM) and cumulative APAR (Fig. 6). APAR is the product of E_i , E_s , and S from [1]. The relationship between PM and APAR, which has been forced through the intercept, is presented in Table 2. It is described by the equation $PM = 2.77 * APAR$ ($R^2 = 0.98$). The slope did not vary significantly among treatment levels of N.

These results indicate that the primary effect of change in N supply on seasonal phytomass production was a change in E_i and not E_c . Muchow (1985) studying the effects of water deficits on E_c and E_i in soybeans found that with water deficits developing slowly from seedling establishment through maturity, reductions in phytomass production were primarily due to a reduction in E_i and only secondarily to reductions in E_c . In contrast, when water deficits were imposed by terminating irrigation 6 weeks after sowing, reductions in E_c accounted for a larger portion of the reduction in phytomass production than did reductions in E_i . This research and ours would indicate that under field conditions where plants are exposed to moderate water or nutrient deficit conditions for substantial portions of the growing season, E_c is not substantially affected. However when severe deficits,

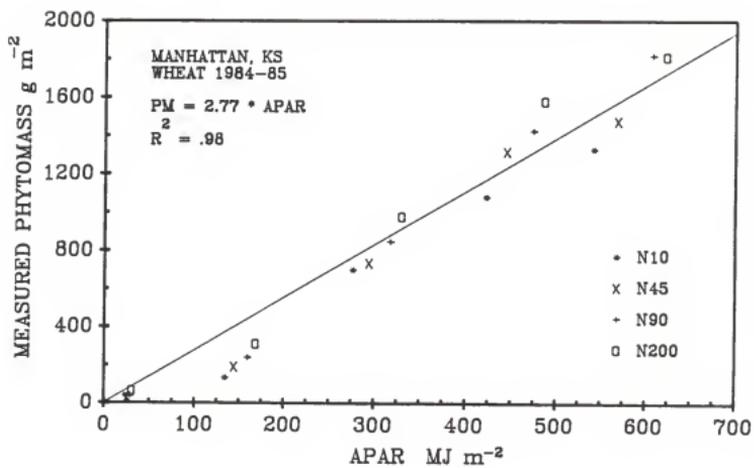


Fig. 6. The relationship between cumulative phytomass production and cumulative APAR.

Table 2. Regression coefficients and 95% confidence limits for the linear model relating APAR to cumulative above ground phytomass production where E_i has been estimated using ND and $APAR = E_i * E_s * S$.

NITROGEN LEVEL	COEFFICIENTS		
	INTERCEPT $g\ m^{-2}$	SLOPE (E_c) $g\ MJ^{-1}$	95% Confidence Interval
N10	-94 + 267.50	2.68	2.13 < E_c < 3.24
N45	-114 ± 268.17	2.92	2.39 < E_c < 3.45
N90	-154 + 269.37	3.23	2.73 < E_c < 3.73
N200	-94 ± 191.20	3.18	2.69 < E_c < 3.67
Pooled	0.0	2.77	2.60 < E_c < 2.94

such as those found in plants which are transplanted from optimum nutrient solutions to N deficient solutions, are imposed on plants which have been growing under optimum conditions the plants cannot modify their canopy rapidly enough to avoid reductions in E_c .

As was noted previously, overestimates of phytomass production early in the season may have been due to a shift in E_c during plant growth. Weiser (1985) found that E_c was not constant in grasslands and suggested that it is dependent upon stage of plant development. We examined this possibility, evaluating the slope of the relationship between PM and APAR over different periods of growth (Table 3). Early in plant growth (double ridge to terminal spikelet) 95% confidence limits for E_c fell within a range of 1.0 to 2.0 $g\ MJ^{-1}$ and were significantly

Table 3. Regression coefficients and 95% confidence limits for the linear models relating APAR to cumulative above ground phytomass during different growth periods.

GROWTH PERIOD	INTERCEPT g M ⁻²	SLOPE g MJ ⁻¹	
DR-TS	-4.2 ± 58.8	1.51 ± 0.54	b*
TS-A	-351.2 ± 111.2	3.76 ± 0.34	a
A-SD	13.9 ± 972.7	2.81 ± 1.85	ab

DR = Double Ridge
 TS = Terminal Spikelet
 A = Anthesis
 SD = Soft Dough

* Coefficients with the same letter are not significantly different

t-test computations:

$$t = \frac{b_1 - b_2}{\sqrt{sb_1^2 - sb_2^2}}$$

H₀: Slope DR-TS = TS-A

$$t = \frac{1.51 - 3.76}{\sqrt{.22^2 + .15^2}} = -8.45$$

$$t_{.05,4} = 2.776$$

$$p < 0.005$$

H₀: Slope A-SD = TS-A

$$t = \frac{2.81 - 3.76}{\sqrt{.75^2 + .15^2}} = -1.24$$

$$t_{.05,4} = 2.776$$

$$p < 0.26$$

H₀: Slope DR-TS = A-SD

$$t = \frac{1.51 - 2.81}{\sqrt{.22^2 + .75^2}} = -1.66$$

$$t_{.05,4} = 2.776$$

$$p < 0.17$$

different from values of E_c during the peak period of growth (terminal spikelet to anthesis) when E_c ranged from 3.3 to 4.1 g MJ⁻¹. Some of these changes in E_c may be attributable to changes in the partitioning of photosynthate through the growing season. During early growth, plants are moving part of their photosynthate to the roots and E_c based upon above-ground phytomass production would be reduced. E_c reduction during the early growth in spring may also be associated with lower temperatures occurring at that time (Appendix, Fig. 5). Mesophyll resistance increases with decreasing temperature and photosynthesis is inversely proportional to mesophyll resistance (Monteith, 1981).

Although E_c during post anthesis growth was not statistically different from that of the peak growth period (due to variability in the data) it did tend to decrease during the period, ranging from 1.3 to 3.0 g MJ⁻¹. Larcher (1983) showed that E_c could be related to the ratio between gross photosynthesis and respiration. After anthesis this ratio becomes smaller due to increases in respiratory activity of senescing foliage. Also, in field experiments it is very difficult to recover all of the senesced material. This loss would result in underestimations of phytomass production. Both of these factors would contribute to the low range of values for E_c during the post anthesis period. It should be noted,

however, that in contrast to the vegetative stage of growth, translocation from the root to the head during this period could offset some of the underestimation in above-ground phytomass production.

Grain Yield and Harvest Index

Final above-ground PM and grain production were significantly greater in Newton, the cultivar most commonly grown in Kansas. PM also responded to increased applications of N. However, grain production was not responsive to increased N and in fact the N200 treatment resulted in the lowest grain yield (Table 4).

Irrigation had no significant effect on any of the yield parameters. Factors which may have had an influence on the results included heavy rains immediately after the only irrigation (Appendix, Fig. 1) and severe lodging in the high N treatments (Appendix, Table 3).

Grain yield is the product of APAR, Ec, and partitioning of PM to the grain (harvest index). The harvest index (HI) varied significantly among N treatments, ranging from 0.27 for the N200 treatment to 0.345 for the N10 treatment (Table 4). This compares with a range of values of 0.29 to 0.60 which were collected from the literature, as reported by Gallagher and Biscoe (1978). The N200 treatment had significantly more kernels per head (Table 4), yet due to low kernel weights the

Table 4. Summary of yield components* and harvest index.

	Weight per Kernel	Kernel per Head	Measured Grain Yield	Above- Ground Phytomass	Harvest Index
	g k ⁻¹	k hd ⁻¹	kg ha ⁻¹	kg ha ⁻¹	
Colt	0.0249	16.3	2335.3	7667.5	0.32
Newton	0.0244	15.8	2768.8	8626.2	0.33
LSD (0.05)	NS	0.4	128.7	326.4	NS
N10	0.0267	15.7	2584.8	7490.5	0.35
N45	0.0265	15.8	2578.0	7686.3	0.34
N90	0.0251	15.9	2707.5	8755.3	0.32
N200	0.0203	16.8	2338.3	8655.2	0.28
LSD (0.05)	0.0010	0.4	282.7	797.3	0.02

* For comparison purposes, measured grain yield has been converted to kg ha⁻¹ (g m⁻² = kg ha⁻¹ * 10). All weights are on an oven-dried basis.

final yield was lowest in this treatment. Lodging which occurred after kernel number had been fixed, but before grain fill took place, contributed to the low kernel weight in the N200 treatment.

Conclusions

Remotely sensed canopy reflectance data effectively estimated E_i and above ground phytomass production. This use of Lapitan's (1986) independently developed equation to convert ND to E_i demonstrates that the procedure can be extended to different seasons and crops grown under different N regimes.

Increased N application resulted in reductions in harvest index (HI) and increased light interception of the crop, with only secondary effects on photochemical efficiency of conversion (E_c). The seasonal (double ridge through soft dough) value of E_c over all treatments was 2.77 g MJ^{-1} with maximum E_c reaching 3.76 g MJ^{-1} during the period of terminal spike through anthesis. This high value for E_c during terminal spikelet through anthesis emphasizes the importance of the growth period to wheat development. Could timing of husbandry inputs to correspond with this period lead to more efficient and economic use of such inputs?

Management practices can affect leaf area expansion and duration but not the rate of photosynthesis per unit

leaf area. Therefore, timing and extent of husbandry inputs should be focused on attainment of rapid leaf expansion and duration rather than maximization of plant N. However, management decisions should account for cultivar characteristics and environmental limitations in order to balance changes in light interception and harvest index for maximum return on inputs.

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APPENDIX

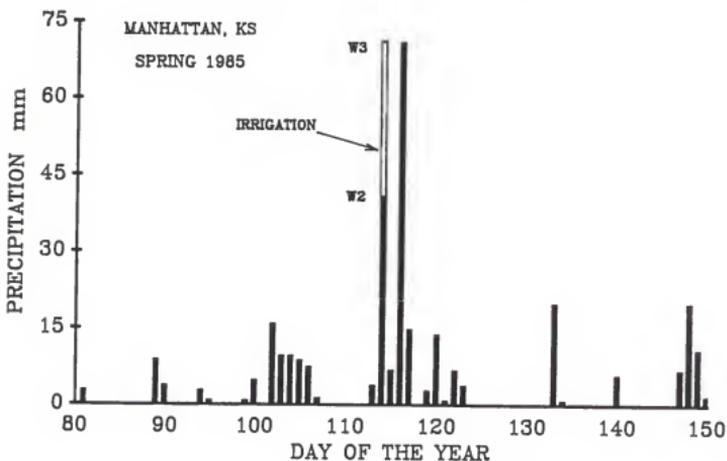
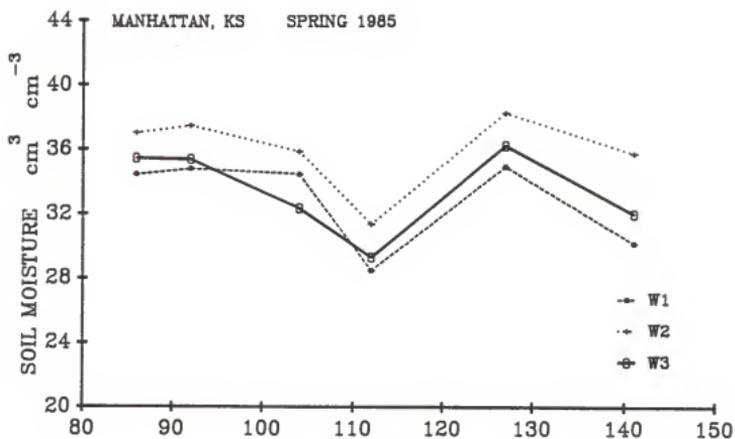


Fig. 1(a). Seasonal patterns of rainfall and soil moisture content, with mean soil moisture content by volume averaged over six depths from the surface to 1.2 m. Data are the mean of eight observations taken from four replications, two N levels (N10, N90), and one cultivar (Colt).

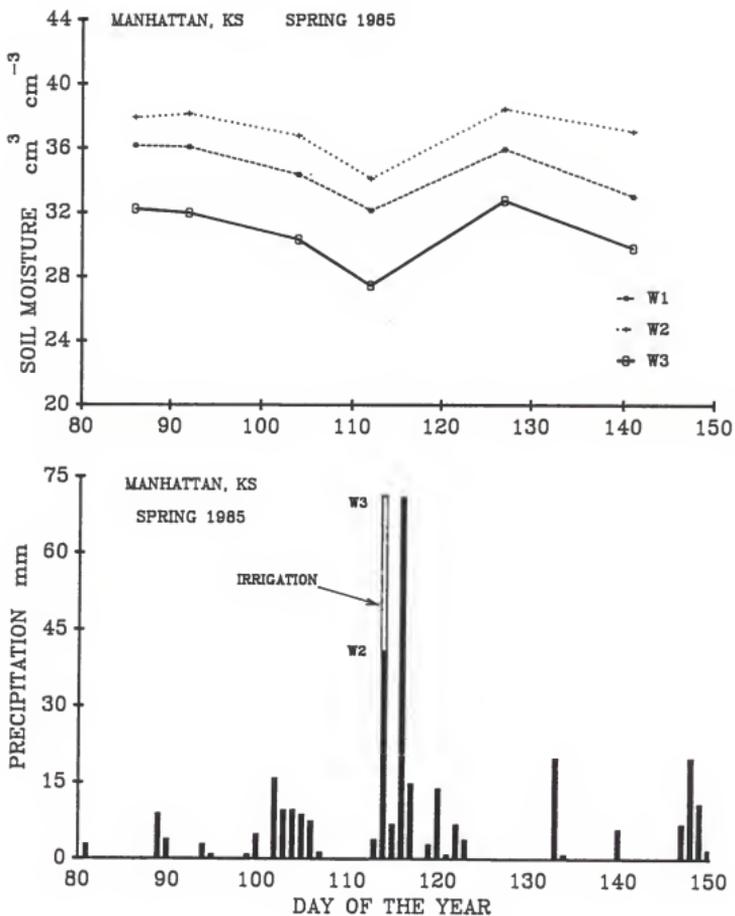


Fig. 1(b). Seasonal patterns of rainfall and soil moisture content, with mean soil moisture content by volume averaged over ten depths from the surface to 2.4 m. Data are the mean of eight observations taken from four replications, two N levels (N10, N90), and one cultivar (Colt).

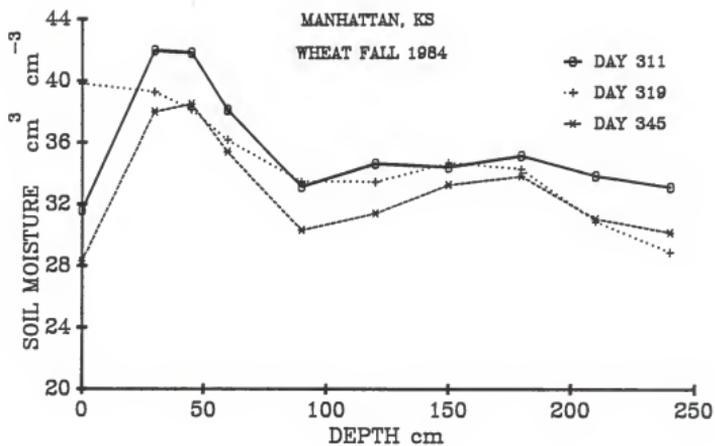


Fig. 2(a). Soil moisture content from surface to 2.4 m, fall 1984. Data are the means of 24 observations taken from four replications, three water levels, two N levels (N10, N90), and one cultivar (Colt).

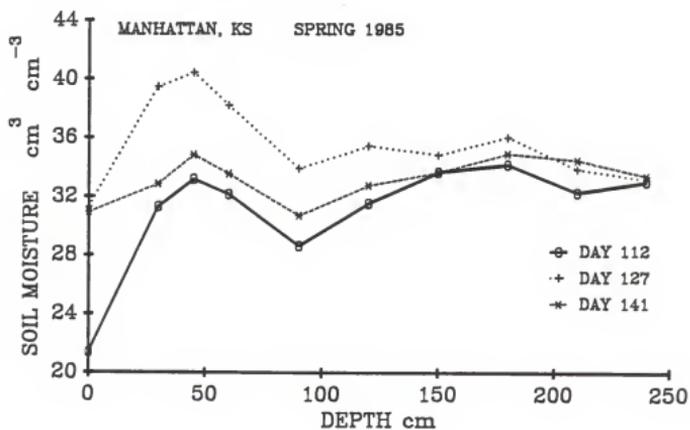
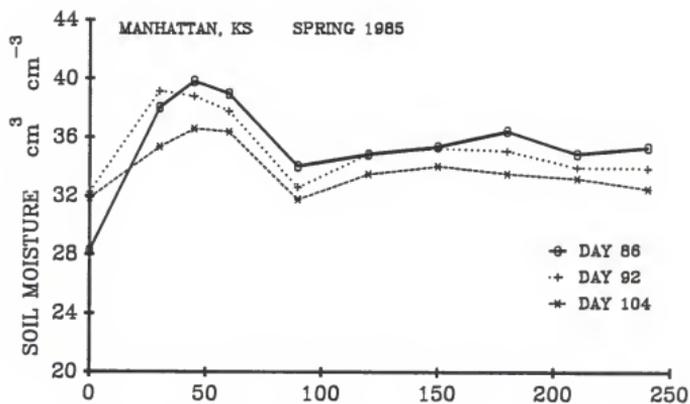


Fig. 2(b). Soil moisture content from surface to 2.4 m, spring 1985. Data are the means of 24 observations taken from four replications, three water levels, two N levels (N10, N90), and one cultivar (Colt).

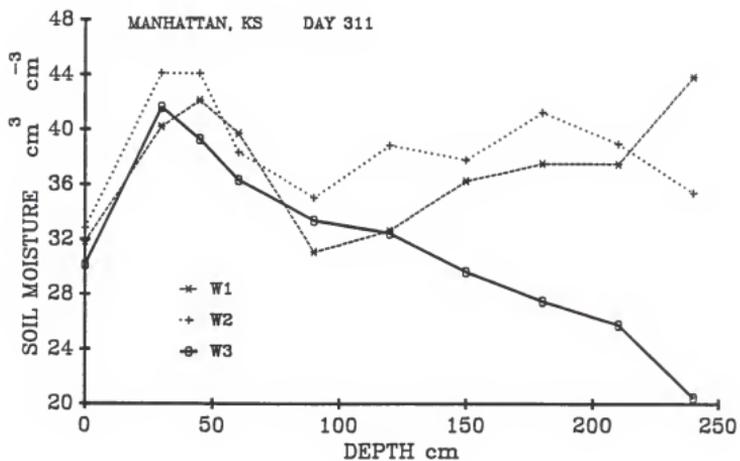


Fig. 3(a). Soil moisture content by water level, day 311. Data are the mean of eight observations taken from four replications, two N levels (N10, N90), and one cultivar (Colt).

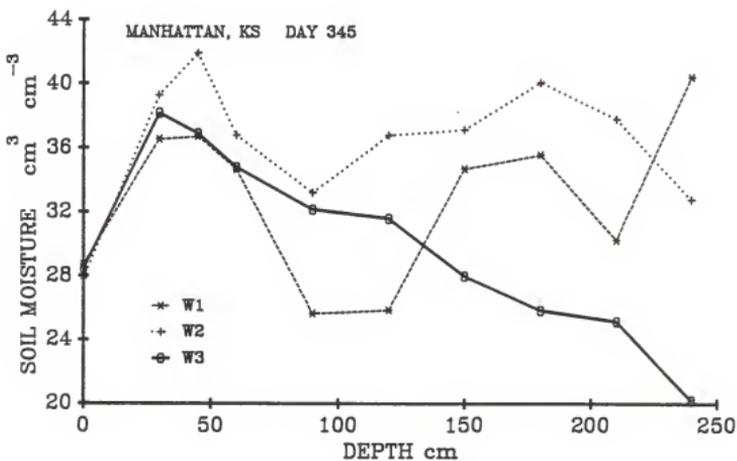
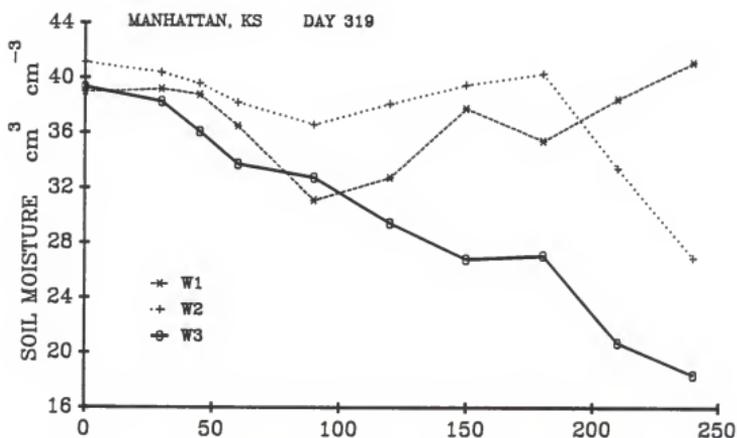


Fig. 3(b). Soil moisture content by water level, days 319 and 345. Data are the mean of eight observations taken from four replications, two N levels (N10, N90), and one cultivar (Colt).

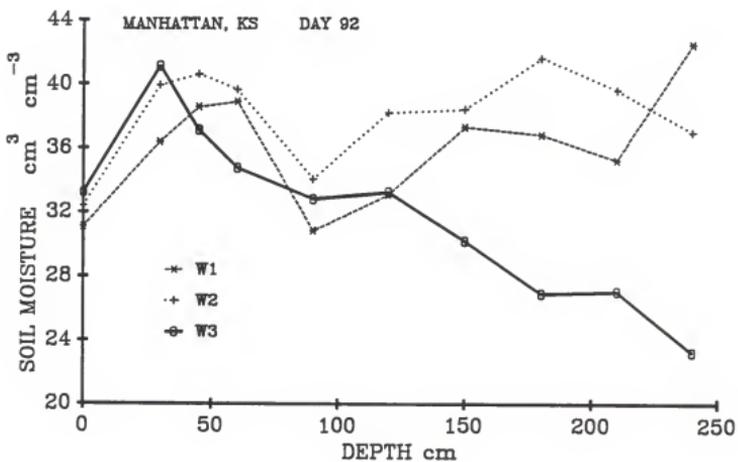
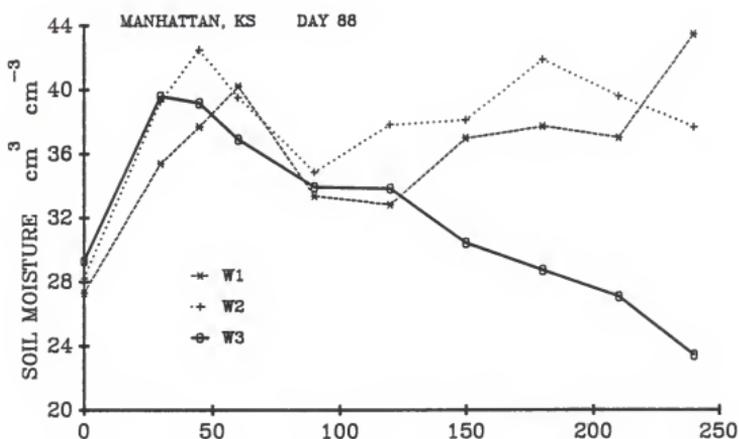


Fig. 3(c). Soil moisture content by water level, days 86 and 92. Data are the mean of eight observations taken from four replications, two N levels (N10, N90), and one cultivar (Colt).

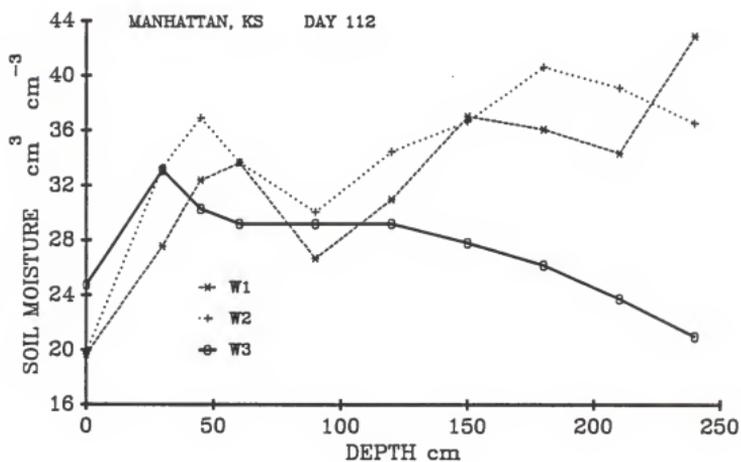
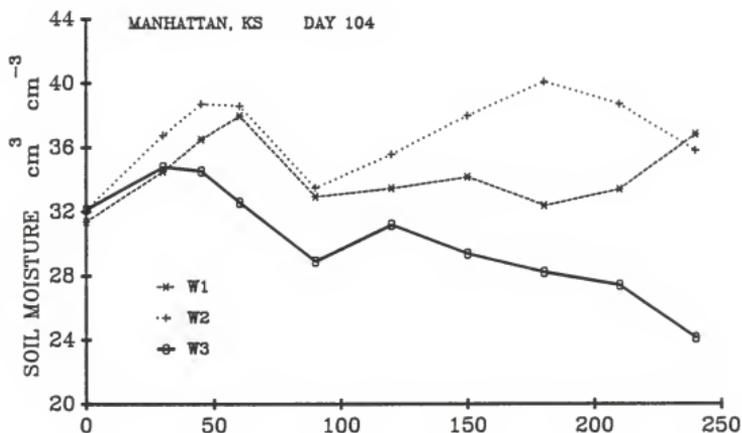


Fig. 3(d). Soil moisture content by water level, days 104 and 112. Data are the mean of eight observations taken from four replications, two N levels (N10, N90), and one cultivar (Colt).

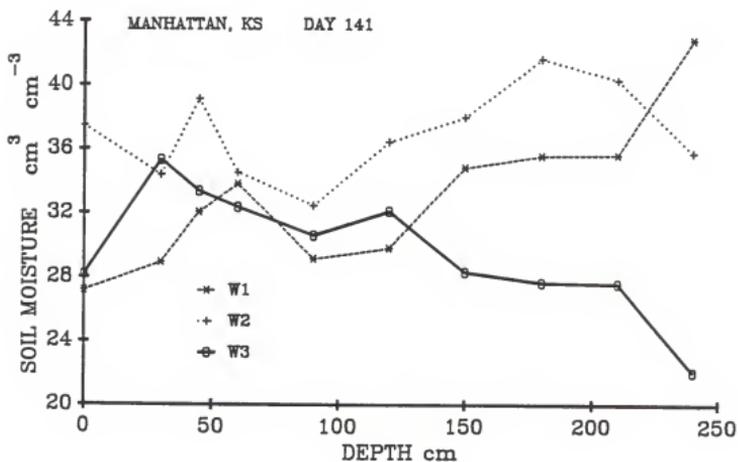
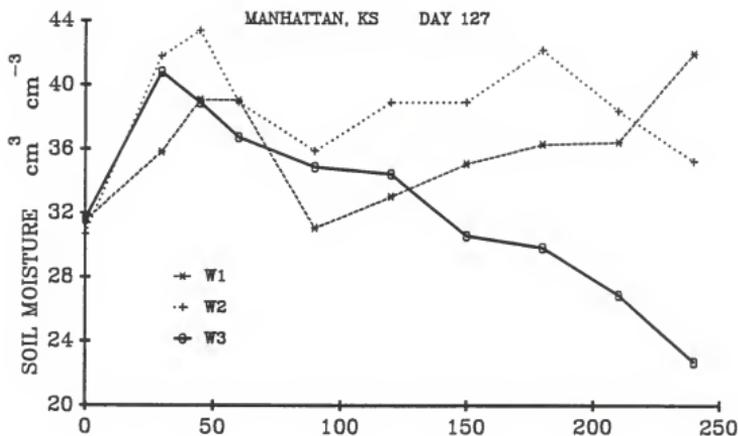


Fig. 3(e). Soil moisture content by water level, days 127 and 141. Data are the mean of eight observations taken from four replications, two N levels (N10, N90), and one cultivar (Colt).

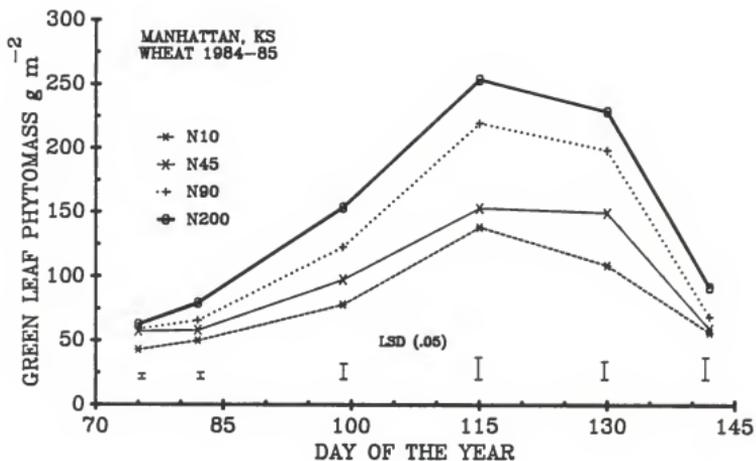


Fig. 4(a). Seasonal changes in green leaf phytomass of winter wheat. Data are means from three water levels, two cultivars, and two replications.

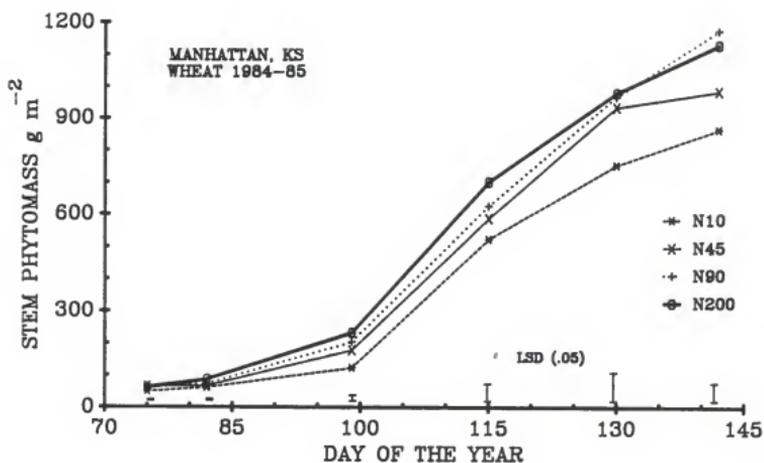


Fig. 4(b). Seasonal changes in stem phytomass of winter wheat. Data are means from three water levels, two cultivars, and two replications.

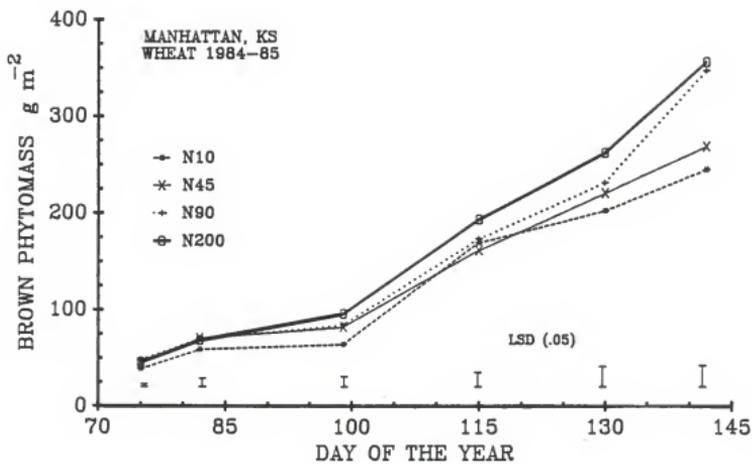


Fig. 4(c). Seasonal changes in brown phytomass of winter wheat. Data are means from three water levels, two cultivars, and two replications.

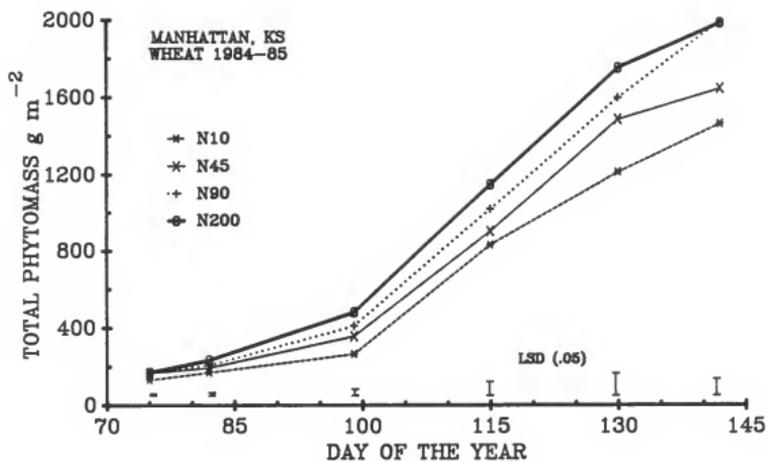


Fig. 4(d). Seasonal changes in total phytomass of winter wheat. Data are means from three water levels, two cultivars, and two replications.

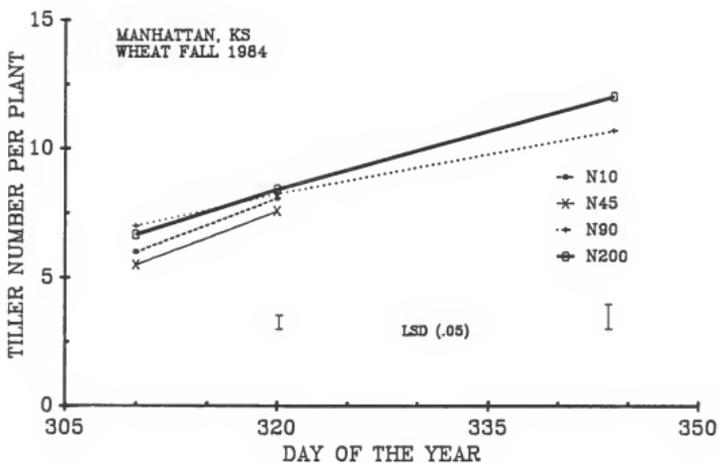


Fig. 4(e). Changes in tiller number of winter wheat during fall growth. Data are means from three water levels, two cultivars, and two replications.

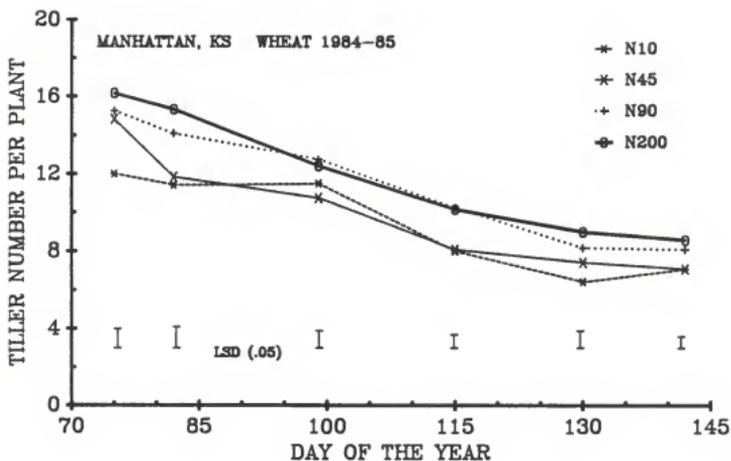


Fig. 4(f). Changes in tiller number of winter wheat during spring growth. Data are means from three water levels, two cultivars, and two replications.

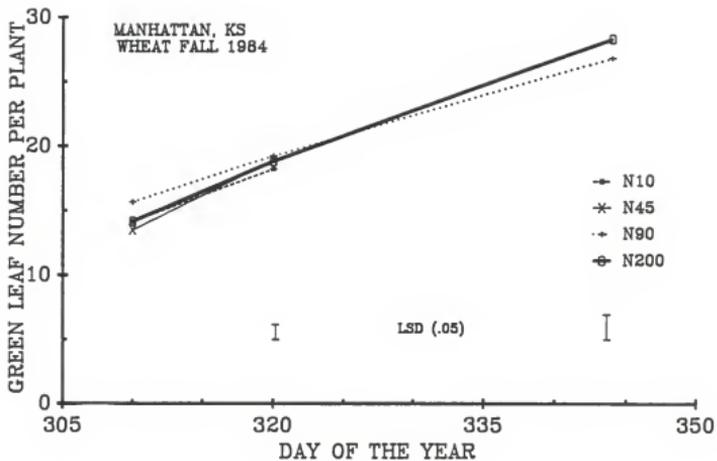


Fig. 4(g). Changes in green leaf number of winter wheat during fall growth. Data are means from three water levels, two cultivars, and two replications.

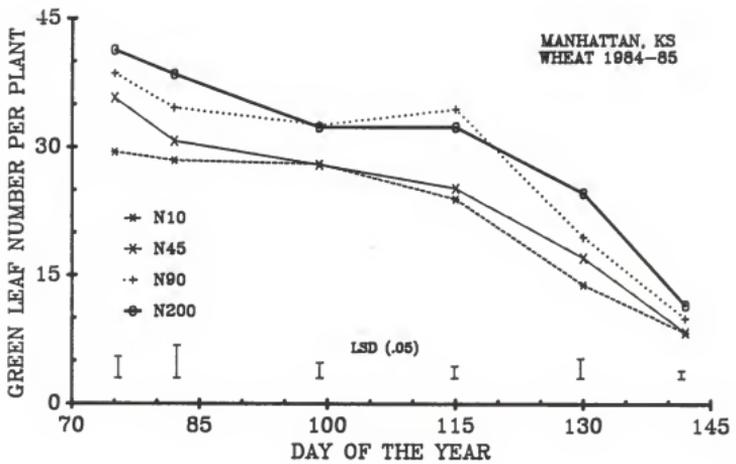


Fig. 4(h). Changes in green leaf number of winter wheat during spring growth. Data are means from three water levels, two cultivars, and two replications.

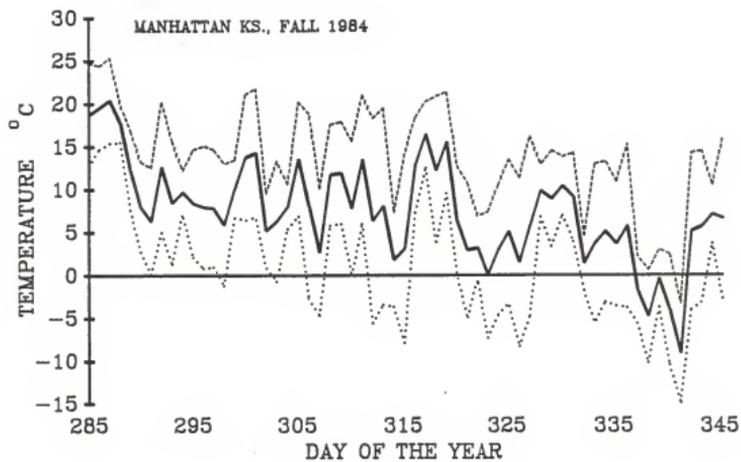


Fig.5(a). Daily maximum, minimum, and mean temperatures, Fall 1984.

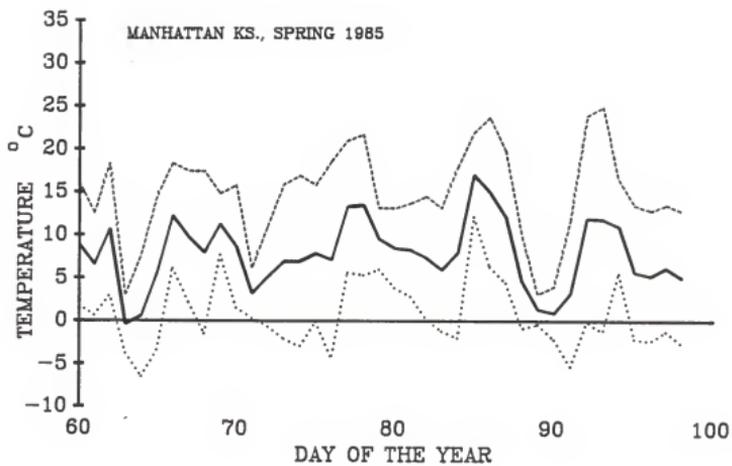


Fig. 5(b). Daily maximum, minimum, and mean temperatures, Spring 1985 (through terminal spikelet).

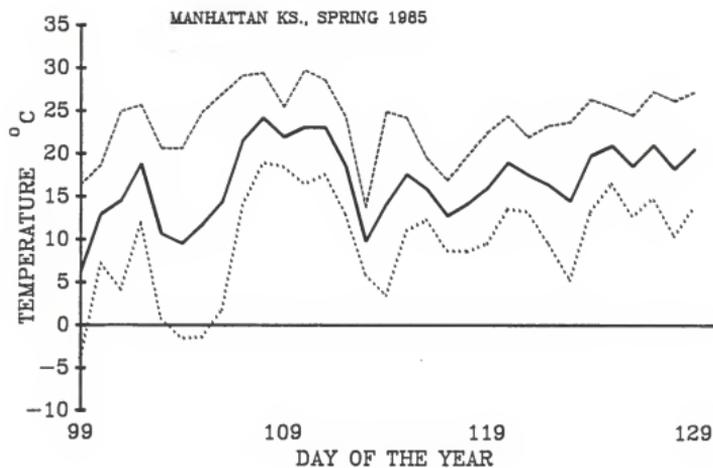


Fig. 5(c). Daily maximum, minimum, and mean temperatures, Spring 1985 (terminal spikelet to anthesis).

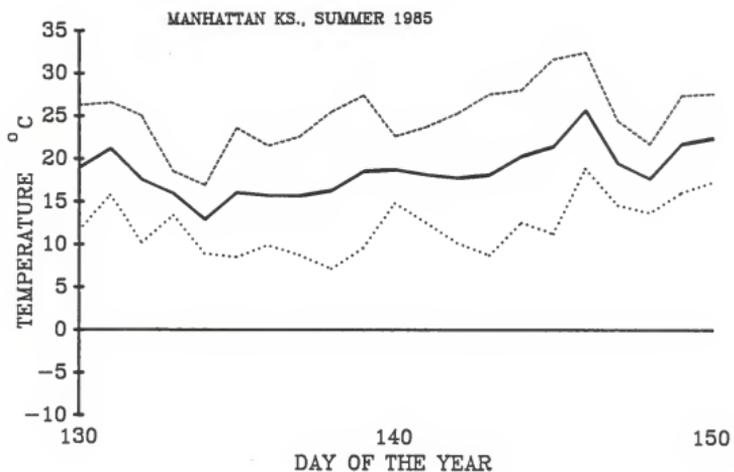


Fig. 5(d). Daily maximum, minimum, and mean temperatures, Spring 1985 (anthesis through soft dough).

Table 1. Plant populations, November 1, 1984.

		PLANTS /m ² on Replication III		
		<u>W1</u>	<u>W2</u>	<u>W3</u>
N10	C1	132	145	143
	C2	133	150	132
N45	C1	150	140	154
	C2	142	138	140
N90	C1	142	145	162
	C2	137	145	125
N200	C1	143	136	154
	C2	126	143	136

W: 1 = Non-irrigated
 2 = 1 irrigation, 4 cm
 3 = 1 irrigation, 7 cm

N: N10 = 10 kg ha⁻¹
 N45 = 45 kg ha⁻¹
 N90 = 90 kg ha⁻¹
 N200 = 200 kg ha⁻¹

C: 1 = Colt, 2 = Newton

Table 2. Growth stages.

CALENDAR DATE	DAY	GROWTH STAGE SCALES		DESCRIPTION
		HAUN	Z-C-R ^a	
11/05/84	310	3.0	24	Seedling growth
03/11/85*	70	Vegetative stage		Figure 5.17 ^b
03/18/85	77	3.5	26	Tillering
03/18/85*	77	Double ridge		Figure 5.18
03/22/85	81	4.0	28	Tillering
03/26/85	85	4.4	30	Tillering
04/03/85	93	5.0	33	Tillering, stem elongation
04/05/85*	95	Floret primordium		Figures 5.24 and 5.25
04/09/85	99	5.5	35	Stem elongation
04/11/85*	101	Terminal spikelet		Figures 5.27 and 5.28
04/17/85	107	6.2	37	Stem elongation
04/22/85	112	6.8	39	Stem elongation
05/03/85	123	9.1	49	Flagleaf extension, boot
05/09/85	129	10.4	62	Heading, early anthesis
05/12/85	132	10.8	68	Anthesis, water ripe
05/21/85	141	-	74	Soft dough
05/31/85	151	-	88	Hard dough, mature

* Dissections

^a Zadoks-Chang-Konzak

^b Figures are from Kirby, E.J.M. and M. Appleyard, 1981. Cereal development guide. National Agricultural Centre, Stoneleigh, England.

Table 3. Lodging scores.

TREATMENT LEVEL			DATES			
C	N	W	05/10/85 130	05/19/85 139	06/04/85 155	07/01/85 185
(percentage of treatment)						
1	10	1	-	-	-	-
1	10	2	-	-	-	-
1	10	3	-	-	-	-
1	45	1	-	-	-	-
1	45	2	-	-	-	-
1	45	3	-	-	6	10
1	90	1	-	-	-	-
1	90	2	-	-	21	35
1	90	3	-	-	24	40
1	200	1	30	35	50	60
1	200	2	30	35	62	80
1	200	3	30	50	65	85
2	10	1	-	-	-	-
2	10	2	-	-	-	-
2	10	3	-	-	-	-
2	45	1	-	-	-	-
2	45	2	-	-	-	-
2	45	3	-	-	3	5
2	90	1	-	-	-	-
2	90	2	-	-	15	25
2	90	3	-	-	12	20
2	200	1	-	-	-	-
2	200	2	10	18	28	40
2	200	3	5	10	23	35

C: 1 = Colt, 2 = Newton

W: 1 = Dryland; 2 = 1 irrigation, 4 cm;

3 = 1 irrigation, 7 cm

Table 4(a). Summary of statistical analysis of neutron probe soil moisture data to 2.4 m.

DAY	N	D	N*W	N*D	W*D	N*W*D
311	NS	**	NS	NS	**	NS
319	NS	**	NS	NS	**	NS
345	NS	**	NS	NS	**	NS
86	NS	**	NS	NS	**	NS
92	NS	**	NS	NS	**	NS
104	NS	**	NS	NS	**	NS
112	NS	**	NS	NS	**	NS
127	NS	**	NS	NS	**	NS
141	NS	NS	NS	NS	**	NS

*,** Significant at the 0.05 and 0.01 probability level, respectively.

W = Water, N = Nitrogen, D = Depth.

Table 4(b). Summary of statistical analysis of neutron probe soil moisture data to 1.2 m depth.

DAY	N	D	N*W	N*D	W*D	N*W*D
311	NS	**	NS	NS	NS	NS
319	NS	**	NS	NS	NS	NS
345	NS	**	NS	NS	NS	NS
86	NS	**	NS	NS	NS	NS
92	NS	**	NS	NS	NS	NS
104	NS	**	NS	NS	NS	NS
112	NS	**	NS	NS	*	NS
127	NS	**	NS	NS	NS	NS
141	NS	NS	NS	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability level, respectively.

W = Water, N = Nitrogen, D = Depth.

Table 5(a). Means of soil moisture content in water blocks over all depths and nitrogen treatments to 2.4 m.

DAY	WATER TREATMENT	SOIL MOISTURE
		cm ³ cm ⁻³
311	1	37.23
311	2	38.64
311	3	31.63
319	1	36.98
319	2	37.52
319	3	30.25
345	1	32.69
345	2	36.37
345	3	30.10
86	1	36.16
86	2	37.91
86	3	32.18
92	1	35.96
92	2	38.14
92	3	31.97
104	1	34.33
104	2	36.70
104	3	30.46
112	1	31.82
112	2	34.08
112	3	27.43
127	1	35.90
127	2	38.43
127	3	32.72
141	1	32.95
141	2	36.98
141	3	29.73

Table 5(b). Means of soil moisture content in water blocks over all depths and nitrogen treatments to 1.2 m.

DAY	WATER TREATMENT	SOIL MOISTURE	
		cm ³	cm ⁻³
311	1	36.24	
311	2	38.85	
311	3	35.51	
319	1	36.20	
319	2	38.98	
319	3	34.92	
345	1	33.26	
345	2	35.94	
345	3	33.65	
86	1	34.45	
86	2	37.02	
86	3	35.30	
92	1	34.81	
92	2	37.47	
92	3	35.38	
104	1	34.44	
104	2	35.85	
104	3	32.37	
112	1	28.48	
112	2	31.34	
112	3	29.28	
127	1	34.91	
127	2	38.24	
127	3	36.21	
141	1	30.14	
141	2	35.71	
141	3	31.97	

Table 6(a). Summary of statistical analysis of plant component data.

DAY	N	C	N*C	N*W	C*W	N*W*C
<u>TOTAL PHYTOMASS</u>						
320	*	NS	NS	NS	NS	*
344	NS	NS	NS	NS	NS	NS
75	*	NS	NS	NS	NS	*
82	*	NS	NS	NS	NS	NS
99	**	NS	NS	NS	NS	NS
115	*	NS	**	NS	NS	**
130	**	NS	NS	NS	NS	NS
142	**	NS	*	NS	NS	NS
<u>LEAF PHYTOMASS</u>						
320	*	NS	NS	NS	NS	NS
344	NS	NS	NS	NS	NS	NS
75	**	*	**	*	NS	*
82	**	NS	NS	NS	NS	NS
99	**	NS	NS	NS	NS	NS
115	**	NS	NS	NS	NS	NS
130	**	*	NS	*	NS	NS
142	**	**	**	NS	NS	*

*,** Significant at the 0.05 and 0.01 probability level, respectively

Table 6(b). Summary of statistical analysis of plant component data.

DAY	N	C	N*C	N*W	C*W	N*W*C
<u>STEM PHYTOMASS</u>						
320	NS	NS	NS	NS	NS	NS
344	NS	NS	NS	NS	NS	NS
75	*	*	NS	NS	NS	NS
82	*	NS	NS	NS	NS	NS
99	**	NS	NS	NS	NS	NS
115	NS	NS	**	NS	**	**
130	NS	NS	NS	NS	NS	NS
142	**	NS	NS	NS	NS	NS
<u>BROWN PHYTOMASS</u>						
320	NS	NS	NS	NS	NS	NS
344	NS	NS	NS	NS	NS	NS
75	NS	NS	NS	NS	**	NS
82	NS	NS	NS	NS	NS	NS
99	NS	NS	NS	NS	NS	NS
115	NS	NS	NS	NS	NS	NS
130	NS	*	NS	NS	NS	NS
142	**	NS	NS	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability level, respectively

Table 6(c). Summary of statistical analysis of plant component data.

DAY	N	C	N*C	N*W	C*W	N*W*C
<u>HEAD PHYTOMASS</u>						
320	-	-	-	-	-	-
344	-	-	-	-	-	-
75	-	-	-	-	-	-
82	-	-	-	-	-	-
99	-	-	-	-	-	-
115	-	-	-	-	-	-
130	NS	**	NS	NS	NS	*
142	**	**	NS	NS	NS	NS
<u>HEAD NUMBER</u>						
320	-	-	-	-	-	-
344	-	-	-	-	-	-
75	-	-	-	-	-	-
82	-	-	-	-	-	-
99	-	-	-	-	-	-
115	-	-	-	-	-	-
130	NS	NS	NS	NS	NS	NS
142	*	NS	NS	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability level, respectively

Table 6(d). Summary of statistical analysis of plant component data.

DAY	N	C	N*C	N*W	C*W	N*W*C
<u>LEAF NUMBER</u>						
320	NS	NS	NS	NS	NS	NS
344	NS	NS	NS	NS	NS	NS
75	**	**	NS	**	NS	NS
82	NS	*	NS	NS	NS	NS
99	NS	**	*	NS	NS	NS
115	**	*	NS	*	NS	NS
130	**	**	NS	NS	NS	NS
142	*	**	NS	NS	NS	NS
<u>TILLER NUMBER</u>						
320	NS	NS	NS	NS	NS	NS
344	NS	NS	NS	NS	NS	NS
75	*	**	NS	*	NS	NS
82	*	*	NS	NS	NS	NS
99	NS	*	NS	NS	NS	NS
115	*	NS	NS	NS	NS	NS
130	NS	NS	NS	NS	NS	NS
142	.067	NS	NS	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability level, respectively

Table 6(e). Summary of statistical analysis of plant component data.

DAY	N	C	N*C	N*W	C*W	N*W*C
<u>GROWING LEAF AREA</u>						
320	NS	NS	NS	NS	*	NS
344	NS	NS	NS	NS	NS	NS
75	**	*	NS	**	NS	NS
82	.07	NS	NS	NS	NS	NS
99	**	NS	**	NS	NS	*
115	**	*	NS	NS	NS	NS
130	**	NS	NS	NS	NS	*
142	**	*	NS	NS	NS	NS
<u>FLAG LEAF AREA</u>						
320	-	-	-	-	-	-
344	-	-	-	-	-	-
75	-	-	-	-	-	-
82	-	-	-	-	-	-
99	-	-	-	-	-	-
115	NS	NS	NS	NS	NS	NS
130	**	NS	NS	*	**	**
142	*	NS	NS	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability level, respectively

Table 7(a). Effect of nitrogen supply on the growth of plant components; Fall 1984.

DAY	NITROGEN LEVEL	PHYTOMASS $g\ m^{-2}$				COUNT PER PLANT			LEAF AREA INDEX		
		LEAF	STEM	DEAD	HEAD	TOTAL	LEAF	TILLER	HEAD	GREEN	FLAG
310	10	8.8	22.1	0.9	-	31.8	14.2	6.0	-	0.47	-
310	45	15.3	21.2	1.0	-	37.5	13.5	5.5	-	0.51	-
310	90	10.0	21.6	1.6	-	33.1	15.7	7.0	-	0.57	-
310	200	9.1	19.7	0.6	-	29.4	14.2	6.7	-	0.52	-
320	10	9.9	30.1	2.3	-	42.3	18.3	8.1	-	0.59	-
320	45	12.2	33.9	2.4	-	48.5	18.9	7.6	-	0.71	-
320	90	20.7	36.6	2.3	-	59.5	19.3	8.3	-	0.68	-
320	200	16.0	35.3	2.7	-	54.0	18.8	8.4	-	0.71	-
	LSD	2.4	3.2	0.4	-	3.9	1.2	0.5	-	0.04	-
344	10	NO EST	NO EST	NO EST	-	NO EST	NO EST	NO EST	-	NO EST	-
344	45	NO EST	NO EST	NO EST	-	NO EST	NO EST	NO EST	-	NO EST	-
344	90	32.0	60.3	5.7	-	98.1	26.8	10.7	-	0.94	-
344	200	21.5	54.8	6.0	-	82.3	28.3	12.0	-	0.86	-
	LSD	6.0	13.7	0.6	-	15.0	2.0	1.0	-	0.07	-

LSD ($p < 0.05$)

Table 7(b). Effect of nitrogen supply on the growth of plant components; Spring through terminal spikelet.

DAY	NITROGEN LEVEL	PHYTOMASS $g\ m^{-2}$				COUNT PER PLANT		LEAF AREA INDEX			
		LEAF	STEM	DEAD	HEAD	TOTAL	LEAF	TILLER	HEAD	GREEN	FLAG
75	10	42.9	49.1	38.8	-	130.9	29.4	12.0	-	0.57	-
75	45	57.3	64.8	44.9	-	167.0	35.8	14.8	-	0.78	-
75	90	59.1	62.4	48.6	-	170.0	38.6	15.3	-	0.77	-
75	200	62.5	61.2	45.7	-	169.4	41.3	16.2	-	0.93	-
	LSD	4.0	4.4	3.0	-	10.2	2.5	1.0	-	0.06	-
82	10	49.9	60.9	59.0	-	169.9	28.4	11.4	-	0.78	-
82	45	58.0	66.1	70.5	-	194.7	30.7	11.8	-	0.87	-
82	90	65.5	72.3	70.0	-	207.8	34.6	14.1	-	1.02	-
82	200	79.2	86.2	68.1	-	233.5	38.5	15.3	-	1.19	-
	LSD	4.7	5.9	8.9	-	16.2	3.8	1.1	-	0.13	-
99	10	78.0	123.1	64.1	-	265.2	28.0	11.5	-	1.66	-
99	45	97.4	178.0	82.1	-	357.5	27.9	10.8	-	1.57	-
99	90	122.6	204.0	84.1	-	410.7	32.6	12.8	-	2.10	-
99	200	153.5	232.7	95.6	-	481.7	32.3	12.4	-	2.39	-
	LSD	12.2	17.6	10.7	-	33.5	1.8	0.9	-	0.18	-

LSD (p < 0.05)

Table 7(c). Effect of nitrogen supply on the growth of plant components; terminal spikelet through soft dough.

DAY	NITROGEN LEVEL	PHYTOMASS $g\ m^{-2}$					COUNT PER PLANT			LEAF AREA INDEX	
		LEAF	STEM	DEAD	HEAD	TOTAL	LEAF	TILLER	HEAD	GREEN	FLAG
115	10	137.8	522.7	169.3	-	829.8	23.9	8.0	-	1.68	0.37
115	45	152.7	586.4	161.4	-	900.5	25.2	8.1	-	2.03	0.52
115	90	219.0	625.3	173.1	-	1017.4	34.4	10.3	-	3.58	0.67
115	200	253.4	700.6	193.1	-	1147.1	32.3	10.2	-	3.31	0.39
	LSD	17.0	53.3	15.1	-	72.5	1.4	0.7	-	0.39	0.14
130	10	108.2	752.6	202.0	148.4	1211.2	13.9	6.4	6.2	1.64	0.71
130	45	148.9	933.6	220.2	181.3	1484.0	17.1	7.4	6.9	1.96	0.74
130	90	197.8	966.7	231.0	199.9	1595.3	19.5	8.2	7.8	3.12	1.19
130	200	228.1	978.4	261.7	280.9	1749.1	24.7	9.0	7.5	4.35	1.45
	LSD	14.0	88.4	21.3	39.8	114.3	2.3	0.9	0.7	0.33	0.10
142	10	56.2	863.2	244.3	297.1	1460.9	8.3	7.1	7.1	0.69	0.54
142	45	59.1	982.9	268.0	332.9	1642.9	8.3	7.1	7.4	0.70	0.58
142	90	68.4	1172.2	346.6	402.4	1989.7	9.9	8.1	9.0	0.83	0.63
142	200	91.5	1127.4	355.4	407.5	1981.8	11.5	8.6	8.0	1.24	0.91
	LSD	7.6	55.7	22.4	20.3	85.7	0.9	0.6	0.4	0.12	0.08

LSD ($p < 0.05$)

Table 7(d). Effect of water supply on the growth of plant components.

DAY	WATER LEVEL	PHYTOMASS $g\ m^{-2}$					COUNT PER PLANT				LEAF AREA INDEX	
		LEAF	STEM	DEAD	HEAD	TOTAL	LEAF	TILLER	HEAD	GREEN	FLAG	
310	1	12.5	21.9	1.2	-	35.6	14.8	6.4	-	0.59	-	
310	2	11.2	20.9	0.8	-	33.0	14.4	6.0	-	0.53	-	
310	3	8.6	20.7	1.0	-	30.3	14.0	6.5	-	0.43	-	
320	1	17.2	37.6	2.6	-	57.4	20.6	8.7	-	0.77	-	
320	2	15.1	33.9	1.9	-	50.9	18.8	8.0	-	0.66	-	
320	3	11.8	30.3	2.8	-	44.9	17.0	7.6	-	0.58	-	
344	1	NO EST	NO EST	NO EST	-	NO EST	NO EST	NO EST	-	NO EST	-	
344	2	NO EST	NO EST	NO EST	-	NO EST	NO EST	NO EST	-	NO EST	-	
344	3	18.3	47.6	5.4	-	71.3	24.3	10.4	-	0.71	-	
75	1	55.6	61.6	44.7	-	161.9	35.9	13.8	-	0.77	-	
75	2	57.3	61.2	44.7	-	163.2	38.3	15.1	-	0.79	-	
75	3	53.5	55.3	44.0	-	152.8	34.6	14.8	-	0.72	-	
82	1	63.6	72.3	65.2	-	201.1	32.8	13.7	-	1.00	-	
82	2	57.9	68.6	61.0	-	187.5	31.0	12.8	-	0.92	-	
82	3	68.1	73.3	74.4	-	215.8	35.4	13.1	-	0.97	-	

Table 7(e). Effect of water supply on the growth of plant components.

DAY	WATER LEVEL	PHYTOMASS $g\ m^{-2}$				COUNT PER PLANT			LEAF AREA INDEX		
		LEAF	STEM	DEAD	HEAD	TOTAL	LEAF	TILLER	HEAD	GREEN	FLAG
99	1	108.2	188.8	87.3	-	384.3	28.9	11.8	-	1.89	-
99	2	112.1	175.9	84.5	-	372.5	31.2	11.6	-	1.99	-
99	3	118.2	188.7	72.6	-	379.6	30.5	12.2	-	1.91	-
115	1	180.3	599.7	182.5	-	962.6	27.9	8.6	-	2.34	0.49
115	2	179.0	621.2	167.1	-	967.2	25.6	8.7	-	2.20	0.45
115	3	213.0	605.3	173.1	-	991.3	33.4	10.1	-	3.41	0.53
130	1	184.1	843.9	228.8	181.3	1403.0	15.8	7.1	6.7	2.05	0.80
130	2	173.2	882.5	233.0	232.1	1520.8	20.6	7.6	6.7	3.05	1.10
130	3	190.0	997.1	224.4	194.5	1606.0	19.9	8.5	8.0	3.20	1.17
142	1	51.5	928.3	298.1	349.5	1627.5	8.4	6.9	7.4	0.78	0.62
142	2	72.8	1054.0	305.1	357.4	1789.3	9.5	8.1	8.0	0.79	0.61
142	3	82.2	1127.0	307.4	373.0	1889.6	10.6	8.1	8.2	1.03	0.76

Table 7(f). Effect of cultivar on the growth of plant components.

DAY	CUL	PHYTOMASS $g\ m^{-2}$					COUNT PER PLANT					LEAF AREA INDEX	
		LEAF	STEM	DEAD	HEAD	TOTAL	LEAF	TILLER	HEAD	GREEN	FLAG		
310	1	11.4	21.1	1.0	-	33.5	14.1	6.2	-	0.58	-	-	
310	2	10.2	21.3	1.0	-	32.4	14.7	6.4	-	0.46	-	-	
320	1	15.1	35.6	2.7	-	53.4	18.5	8.1	-	0.71	-	-	
320	2	14.3	32.4	2.1	-	48.7	19.2	8.1	-	0.63	-	-	
344	1	NO EST	NO EST	NO EST	-	NO EST	NO EST	NO EST	-	NO EST	-	-	
344	2	NO EST	NO EST	NO EST	-	NO EST	NO EST	NO EST	-	NO EST	-	-	
75	1	51.8	55.0	44.7	-	151.5	29.9	11.8	-	0.69	-	-	
75	2	59.1	63.7	44.3	-	167.1	42.7	17.3	-	0.84	-	-	
82	1	62.9	71.7	67.2	-	201.8	30.0	12.0	-	1.00	-	-	
82	2	63.5	71.1	66.6	-	201.2	36.0	14.4	-	0.93	-	-	
99	1	107.6	176.9	82.7	-	367.2	26.9	10.7	-	1.92	-	-	
99	2	118.1	192.0	80.3	-	390.4	33.5	13.0	-	1.93	-	-	
115	1	180.3	592.4	174.1	-	946.8	25.6	8.5	-	2.22	0.55	-	
115	2	201.2	625.0	174.4	-	1000.6	32.3	9.7	-	3.08	0.43	-	
130	1	158.9	954.6	247.7	240.5	1601.7	16.7	7.6	7.2	2.71	1.03	-	
130	2	182.6	861.0	209.7	164.7	1418.1	20.8	7.9	7.0	2.82	1.02	-	
142	1	58.9	1053.9	307.1	392.3	1812.2	7.8	7.3	7.4	0.70	0.64	-	
142	2	78.7	1019.0	300.0	327.7	1725.4	11.2	8.1	8.4	1.03	0.68	-	

Table 8. Statistical analysis of harvest data.

	N	C	N*C	N*W	C*W	N*W*C
Protein %	**(.63) ^a	NS	**(.69)	NS	NS	NS
Grain Yield	NS	**(.129)	*(.55)	NS	NS	NS
TDM	**(.797)	**(.326)	NS	NS	NS	NS
Kernel Wt.	**(.1.06)	NS	**(.1.09)	NS	NS	NS
Plants/m	NS	NS	NS	NS	NS	NS
Heads	NS	NS	NS	NS	NS	NS
Heads/m ²	NS	NS	NS	NS	NS	NS
Kernels	**(.47)	*(.41)	NS	NS	NS	NS
Kernels/m ²	NS	NS	NS	NS	NS	NS
Infertile Kernels	NS	*(.38)	NS	NS	NS	NS
Infertile Kernels/m ²	NS	NS	NS	NS	NS	NS

^aLSD ($p < 0.05$) in brackets.

Table 9. Summary of harvest data.

W	N	Cultivar		Cultivar		Cultivar		Cultivar	
		Colt	Newton	Colt	Newton	Colt	Newton	Colt	Newton
		plants/m ²		heads/m ²		heads/plant		kernels/head	
1	1	132	133	731	863	5.54	6.49	16.26	15.20
	2	150	142	790	782	5.27	5.51	16.47	15.54
	3	142	137	790	984	5.56	7.18	14.86	16.18
	4	143	126	960	879	6.72	6.98	17.63	16.68
2	1	145	150	1000	836	6.90	5.57	15.96	16.02
	2	140	138	810	834	5.79	6.04	16.14	15.44
	3	145	145	925	984	6.38	6.79	16.60	15.60
	4	136	143	933	978	6.86	6.84	16.51	16.52
3	1	143	132	820	909	5.73	6.89	15.67	15.19
	2	154	140	800	794	5.20	5.67	15.80	15.36
	3	162	125	968	972	5.98	7.78	16.54	15.72
	4	154	136	947	846	6.15	6.22	17.20	16.28
		mg/kernel		grain, kg/ha		TDM, kg/ha		protein %	
1	1	28.52	25.94	2109	2740	5780	7353	11.30	12.00
	2	27.47	26.29	2247	2544	6448	7453	11.03	11.83
	3	27.02	25.68	2307	2833	7622	8558	11.63	12.05
	4	20.32	21.63	2038	2709	7973	8623	14.33	13.65
2	1	27.05	26.74	2576	2802	7047	7892	10.85	11.73
	2	26.76	25.63	2539	2842	7303	8474	10.83	11.85
	3	25.26	23.88	2841	2843	8692	9207	11.60	12.05
	4	17.68	21.51	1901	2529	8269	8976	14.65	13.18
3	1	28.07	24.09	2510	2772	7794	9077	10.98	12.43
	2	27.57	25.52	2254	3042	7675	8765	11.48	11.18
	3	24.54	23.96	2712	2709	9330	9123	12.15	11.83
	4	18.52	22.18	1991	2862	8077	10013	14.45	12.80

W: 1 = Dryland; 2 = 1 irrigation, 4 cm; 3 = 1 irrigation, 7 cm.

N: 1 = 10 kg/ha, 2 = 45 kg/ha, 3 = 90 kg/ha, and 4 = 200 kg/ha of applied nitrogen.

Note: All weights are on an oven dry basis.

Table 10. Summary of statistical analysis of canopy reflectance data.

DAY	N	C	N*C	N*W	C*W	N*W*C*
<u>NEAR-IRRED/RED RATIO</u>						
73	**	**	**	NS	NS	NS
77	**	**	*	NS	*	NS
91	**	**	NS	NS	NS	NS
101	**	**	*	NS	NS	NS
105	**	**	*	NS	NS	NS
122	**	**	**	**	*	**
128	**	**	*	NS	NS	NS
131	**	**	NS	NS	NS	NS
132	**	**	*	*	**	*
137	**	**	NS	NS	NS	NS
139	**	**	**	*	NS	NS
142	**	**	*	NS	NS	NS
151	**	NS	NS	NS	NS	NS
<u>NORMALIZED DIFFERENCE</u>						
73	**	**	NS	NS	NS	NS
77	**	**	NS	NS	*	NS
91	**	**	NS	*	NS	NS
101	**	**	**	NS	NS	*
105	**	**	**	*	NS	NS
122	**	**	**	**	NS	NS
128	**	**	*	NS	NS	NS
131	**	**	NS	NS	NS	NS
132	**	**	**	**	**	NS
137	**	**	NS	NS	NS	NS
139	**	**	**	**	**	*
142	**	**	NS	NS	NS	NS
151	**	NS	NS	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability level, respectively.

SPECTRAL REFLECTANCE ESTIMATES OF
LIGHT INTERCEPTION AND PHOTOCHEMICAL EFFICIENCY IN
WHEAT UNDER DIFFERENT NITROGEN REGIMES

by

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ABSTRACT

Many crop growth models require estimates of the quantity of photosynthetically active radiation absorbed (APAR) by the canopy and the efficiency at which APAR is converted to dry matter (Ec). APAR has been estimated using line quantum sensors, tube solarimeters, and leaf area measurements. These measurements are expensive and do not provide indications of spatial variability without extensive sampling. Remote sensing of canopy reflectance has the potential to provide rapid accurate estimates of APAR which account for spatial variability of the crop. The objectives of this study were to determine if previously developed procedures for estimating APAR from canopy reflectance data could be applied to wheat grown under different nitrogen (N) regimes, and to examine the photochemical efficiency of dry matter production (Ec) of the crop. Two cultivars of winter wheat (Triticum aestivum L. cvs. 'Newton' and 'Colt') were planted on a leveled Muir silt loam soil (fine-silty, mixed, mesic Cumulic Haplustoll) at the Evapotranspiration Research site located 6 km south of Manhattan, Kansas (39°09' N and 96°37' W). Treatments consisted of the two cultivars, four levels of applied N (10, 45, 90, and 200 kg ha⁻¹), and three levels of irrigation (non-irrigated, 40 mm, and 70 mm). Remotely sensed canopy reflectance, incident solar radiation (S), and crop growth measurements collected

throughout the growing season were used to estimate APAR, above-ground phytomass (PM), and Ec. Daily values of APAR were determined using spectral estimates of light interception efficiency (Ei) and measurements of S. The products of these daily APAR values and a constant for Ec (2.9 g MJ^{-1}) were integrated over time to estimate PM. The ratio of measured cumulative PM to cumulative APAR formed an estimate of Ec. Seasonal values of Ec (2.77 g MJ^{-1}) did not differ significantly between crops grown under different N regimes. Ec did increase during the growing season from 1.51 g MJ^{-1} during early spring growth to 3.74 g MJ^{-1} during the period of terminal spikelet through anthesis. Harvest index (HI) decreased with increased N application. Grain yield was not significantly different among the N10, N45, and N90 treatments. However, Grain yield, as well as HI, were significantly reduced in the highest N treatment due to lodging.