GROWTH, CANOPY TEMPERATURE, AND SPECTRAL REFLECTANCE OF ALFALFA UNDER DIFFERENT IRRIGATION TREATMENTS

by

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Approved by:

M. B. Kirkham
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To my parents,

Ernie and Roberta;

and

my uncle, James W. Taylor

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CHAPTER 1

EVALUATION OF CANOPY TEMPERATURES OF ALFALFA WITH DIFFERENT IRRIGATION TREATMENTS

ABSTRACT

Alfalfa (*Medicago sativa* L. 'Cody') was grown under seven watering regimes to determine the effect of water on canopy temperature in the Southern Great Plains. Irrigation water (0, 2.5, 5.1, 7.6, 10.2, 12.7, or 15.2 cm) was added after each of three harvests in both 1980 and 1981. Throughout the growth period in both years, soil-water content and canopy temperature were measured using, respectively, a neutron-attenuation probe and an infrared thermometer. Extremes in weather between the summers of 1980 and 1981 enabled comparison of data from a stressed season (1980) with those from a non-stressed season (1981). The relationship between canopy-minus-air temperature (T_c - T_a) versus vapor pressure deficit (VPD) was determined on well-watered alfalfa for 1980 and 1981. In the dry year of 1980, irrigated plots had cooler canopy temperatures than did dryland plots, but differences in temperature due to irrigation level were not apparent. In the wet year of 1981, differences in canopy temperature among irrigated and dryland plots were not evident. In both the dry year and the wet year, T_c - T_a was inversely related to VPD.

INTRODUCTION

Plant temperature has long been recognized as an indicator of plant-water stress. Clum (1926) studied temperatures of turgid and wilted leaves and found differences in temperature between 2 and 3 ^{o}C. Tanner (1963) calculated that a decrease in transpiration of 10% from a full cover of alfalfa-brome in Wisconsin in early September would cause a temperature increase of 1^{o}C. Thus, he said, a measurement of the difference in temperatures among plants might show a difference in transpiration. Ansari and Loomis (1959) found temperatures of leaves covered with vaseline to be 1 to 3^{o}C warmer than transpiring leaves. Hsiao (1973) reported that, given constant meteorological conditions, stomatal closure in response to water stress would cause leaf temperatures to rise due to reduced transpiration. Clark and Hiler (1973) related water stress in cowpeas to leaf-air-temperature differences. They found that stomatal closure increased as water stress developed and closure resulted in increased leaf temperature. Ehrler et al. (1978) observed increasing canopy temperature in wheat with decreasing (more negative) plant-water potential. Difference in canopy temperature between stressed and non-stressed plants was shown to be a reliable indicator of plant-water status.

Plant temperature and stress are related because, if a plant is well watered, the stomata are opened and water evaporating from the stomatal cavity cools the plant. As water becomes limiting, the stomata close to obstruct the evaporation of essential water from within the leaf. Under these conditions, cooling by transpiration is reduced and the temperature of the plant rises.

Tanner (1963) used a radiation thermometer to measure the temperatures of several crop canopies in Wisconsin and found that non-irrigated plants had higher temperatures than irrigated plants. The increased temperature of the stressed plants appeared to be due to stomatal closure. This is consistent with the way water-stressed plants adjust by closing their stomata. Tanner (1963) was probably one of the first scientists to use infrared thermometry to determine canopy temperature. Early models of infared thermometers were cumbersome. In the past five years, light-weight (about 1 kg), hand-held infrared thermometers have become commercially available (Jackson et al., 1980; 1981) and have been used to measure canopy temperatures of several crops.

Gardner et al. (1981) studied the effect of water stress on the canopy temperature of differentially irrigated corn. The daily standard deviation of midday canopy temperatures in fully irrigated plots of corn were about ± 3°C. In non-irrigated plots, it was as large as ± 4.2°C. They concluded that plots which exhibited a standard deviation of above ± 3°C needed to be irrigated.

Clawson and Blad (1982) used canopy-temperature data obtained with a hand-held infrared thermometer to schedule irrigation in corn. They designated plots irrigated according to temperature of the crop the "temperature-scheduled plots." They compared the water-use of plots irrigated to near field capacity to temperature-scheduled plots and suggested that water was used more effectively by the temperature-scheduled plots. The yields of grain of the well-watered plots were not significantly different from those of the temperature-scheduled plots; therefore, they concluded that the temperature-scheduled plots had received adequate water.

Canopy temperature of alfalfa has been measured (Idso et al., 1980; 1981a). In none of those experiments, however, has alfalfa been grown under a distinct series of irrigation regimes. Tanner (1963) suggested that plant temperature measurements could be used to detect moisture-stress differences among plants under different regimes. The object of this experiment, therefore, was to determine if progressive differences in temperature existed among plots of alfalfa subjected to seven graded water treatments. In addition, because plant temperatures are influenced by atmospheric conditions, such as vapor pressure deficit (Idso et al., 1981b; 1981c), as well as soil conditions, the relationship between canopy-air temperature differential and vapor pressure deficit was also determined.

MATERIALS AND METHODS

The experiment was conducted during the summers of 1980 and 1981 at a field site located about 3 km (2 miles) southeast of Manhattan, Kansas. The soil type was Eudora silt loam, classified as a Pachic Haplustoll, fine silty, mixed, mesic (Jantz et al., 1975). Alfalfa (Medicago sativa L. 'Cody') was planted in 1978 on leveled land and 42 plots each measuring 9 m x 9 m were established (Fig. 1.1). Access tubes for neutron-moderation measurements were placed in the center of each plot to a depth of 3.5 m (one tube per plot). Borders of soil enclosed the plots and gated irrigation pipe (20-cm diameter) was set on top of the borders. The experimental area was surrounded by 6 m of 'Cody' alfalfa. The plots were irrigated with 0, 2.5, 5.1, 7.6, 10.2, 12.7, or 15.2 cm of ground water (six replications of each amount) at three different times during each of the two growing seasons (Tables 1.1 and 1.2). The experimental design was a randomized complete block. There were seven water treatments (six levels of irrigation; one dryland) in each of six blocks (six replications). The irrigation levels were gauged using meter sticks to measure the depth of irrigation water received, while the water was being rapidly released through the gated pipe. The alfalfa surrounding the experimental area was soaked with water (amount added not measured) on the dates of irrigation.

In 1980, irrigation water and stored soil water were the main sources of water for the plants because of the dry summer. This contrasted with the summer of 1981, which was wet (Tables 1.3 to 1.6). The National Oceanic and Atmospheric Administration (1980, 1981) characterized June and July of 1980 as one of the "driest" periods on record with "torrid" heat, and June and July of 1981 as having very heavy rains, producing large rainfall totals. The extremes in weather between the summers of 1980 and 1981 enabled comparison of data from a stressed season with those from a non-stressed season.

Throughout the growth period, canopy temperature and neutron-attenuation measurements were taken. Canopy temperature was measured with a hand-held infrared thermometer (Model 44, Telatemp Corp., Fullerton, Calif.), held at an oblique angle to measure upper canopy surfaces (Jackson et al., 1980). Measurements (six per plot) were taken between 12:00 and 15:30 CDT.

Soil-water status, throughout the growing season, was determined at seven-to-ten-day intervals with a neutron-moisture probe. The readings were taken to a depth of 3.2 m, in each of the 42 plots, in increments of 15.2 cm. Fifteen-second-standard counts were taken before and after reading each tube. Total water in the 3.2 m soil profile was determined by adding together the amount of water in each layer (15.2 cm increment) of soil.

Vapor pressure deficit (VPD) was calculated as follows:

$$VPD = e* - e \quad (1)$$

where e* = saturation vapor pressure at air temperature, T, and, e, the ambient vapor pressure in air, equals the following (Rosenberg, 1974, p. 131):

$$RH = e/e* \times 100 \quad (2)$$

and rearranging terms,

$$e = (RH \times e*)/100 \quad (3)$$

Values for e* and e were calculated from information contained in the Smithsonian Meteorological Tables (List, 1951, Table 94). Relative humidity (RH) and ambient-air temperature values were obtained from data provided by the National Weather Bureau and kept in files in the Department of Physics, Kansas State University, Manhattan, Kan.

The data were analyzed by analysis of variance (ANOVA), using a regression approach (Neter and Wasserman, 1974), to be able to present the data for an entire growth period, and to adjust for unequal sample numbers during the late-August-to-September-growth periods for both years. During that time, one plot per treatment (except for the 12.7 cm treatment, which was not measured) was measured. The dates that temperature measurements were made in 1980 were 19, 25, 27, 29 August and 2 September, and, in 1981, the dates were 27 and 30 August and 9 and 17 September. The data presented in the canopy minus air temperature (T_c - T_a) versus vapor pressure deficit (VPD) regression analysis for 1980 represent a mean of six replications (a total of 36 readings per data point) receiving 10.2, 12.7, and 15.2 cm of irrigation water. These data were used to insure that the regression analysis involved well-watered plots only (Idso, et al., 1981a). In the regression analysis of 1981 (the wet year), means of the six replications for all treatments were used in the analysis, because all plots were well-watered. The May harvest data of 1981 were not used because there was alfalfa weevil damage.

RESULTS AND DISCUSSION

The 1980 and 1981 data showed that, in Kansas, crops can be subjected to large variations in weather (Tables 1.3 to 1.6). In 1980, temperatures were generally very hot, and the cumulative rainfall from 20 June to 1 September was 136 mm. In contrast, in 1981, the temperatures were cooler and the rainfall from 20 June to 1 September was three times as much (i.e., 414 mm).

In both years, soil-water content of plots irrigated with 15.2 cm of water was higher than dryland plots (Figs. 1.2 and 1.3). Non-irrigated alfalfa grown in 1980 had to rely mainly on stored soil-water, and the moisture content of the profile generally decreased throughout the summer. In the wet year of 1981, the water requirement of dryland alfalfa seemed to have been adequately supplied by rainfall (Fig. 1.3), and the soil-water content tended to increase with time, instead of decreasing, as it did in 1980.

The differences in weather permitted the study of canopy temperatures of differentially irrigated alfalfa grown under dissimilar conditions. Tables 1.7 and 1.8 show canopy minus air temperature (T_c - T_a) for several days during the 1980 and 1981 growing seasons. In the dry year of 1980, plants grown with irrigation water had cooler temperatures than plants grown dryland (Table 1.7). Between

8 July and 6 August, the average canopy temperatures of non-irrigated plants were warmer than air. Usually the plants irrigated with 15.2 cm of water had the coolest leaf temperature, even though their leaf temperature was not statistically different from that of plants receiving 7.6, 10.2, or 12.7 cm of irrigation water (Table 1.7). In the wet year of 1981, level of irrigation had no significant effect on canopy temperature (Table 1.8).

Positive $T_c - T_a$ values were observed during the April-to-May-growing period of 1981 (Table 1.8). Ambient air temperatures (not shown) were between 22°C and 26°C. Vapor pressure deficits were between 1.6 KPa and 2.4 KPa. Idso et al. (1981a) showed positive $T_c - T_a$ values at low VPD and found a linear relationship between $T_c - T_a$ and VPD for well-watered alfalfa. In fact, some of their data were obtained on the plots used in this experiment. It was assumed that the positive values of $T_c - T_a$ observed in April-to-May of 1981 were a result of low ambient air temperatures and low vapor pressure deficits.

A linear regression of $T_c - T_a$ versus VPD for 1980 resulted in an equation similar to the one obtained by Idso et al. (1981a), who found $T_c - T_a = 0.506 - 1.92\text{VPD}$ (KPa). In our study, the regression equations were:

1980: $T_c - T_a = 1.08 - 1.26\text{VPD}$, $R^2 = 0.60$ (Fig. 1.4)

1981: $T_c - T_a = 6.19 - 3.93\text{VPD}$, $R^2 = 0.85$ (Fig. 1.5)

A t-test of the equality of two regression equations at the 0.05 level of significance (Zar, 1974, p. 228-235) revealed that the intercepts of the 1980 equation and the one obtained by Idso et al. (1981a) were equivalent, but the slopes were significantly different. The 1980 equation was tested against the 1981 equation and the slope and intercept terms were found to be significantly different. Differences between the two equations (1980 versus 1981) were probably due to factors such as energy balance, net radiation, stomatal resistance, and atmospheric boundary differences, as well as the range in temperatures and vapor pressures that existed between the two seasons. Figure 1.6 shows $T_c - T_a$ versus VPD for both the 1980 and 1981 data.

CONCLUSION

When alfalfa was irrigated with different amounts of water (0, 2.5, 5.1, 7.6, 10.2, 12.7, or 15.2 cm per irrigation), differences among canopy temperatures due to different irrigation treatments were evident in a dry year, but not in a wet year. In the dry year, the irrigated plots had a cooler canopy temperature than did dryland plots, but differences in temperature due to level of irrigation water added were not apparent. Therefore, in the dry year, the infrared thermometer differentiated between wet and dry plots, but it did not distinguish differences in wetness of the irrigated plots.

In the dry year of 1980, vapor pressure deficits were high (e.g., 7 KPa, Fig. 1.4). In the wet year of 1981, plants at high vapor pressure deficits (e.g., 3 KPa, Fig. 1.5) had cooler leaf temperatures than plants at low vapor pressure deficits (e.g., 1.2 KPa, Fig. 1.5) had cooler leaf temperatures than plants at low vapor pressure deficits (e.g., 1.2 KPa, Fig. 1.5). In the dry year, $T_c - T_a$ was influenced by both irrigation treatment and vapor pressure deficit, but in the wet year, $T_c - T_a$ was affected only by vapor pressure deficit and not by irrigation treatment.

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Table 1.1. Dates of harvest, irrigation, and neutron-probe measurements in 1980. At harvest, plots were cut.

Date (days after first cut of season)	Harvest	Irrigation	Neutron probe
3 June (1)	x		
11 June (9)			x
13 June (11)		x	
16 June (14)			x
23 June (21)			x
1 July (29)			x
8 July (36)	x		
10 July (38)			x
14 July (42)		x	
17 July (45)			x
28 July (56)			x
6 Aug. (65)	x		
7 Aug. (66)			x
11 Aug. (70)		x	
15 Aug. (74)			x
29 Aug. (88)			x
6 Sept. (96)	x		
8 Sept. (98)			
11 Sept. (101)			x
7 Nov. (156)			x
11 Nov. (160)	x		

Table 1.2. Dates of harvest, irrigation, and neutron-probe measurements in 1981. At harvest, plots were cut.

Date (days after first cut of season)	Harvest	Irrigation†	Neutron probe
26 May (1)	x		x
4 June (10)		x	
5 June (11)		x	
6 June (12)		x	
9 June (15)			x
19 June (25)			x
1 July (37)			x
6 July (42)	x		
8 July (44)		x	x
9 July (45)		x	
10 July (46)		x	
11 July (47)			x
20 July (56)			x
3 Aug. (70)			x
9 Aug. (76)	x		
10 Aug. (77)			x
12 Aug. (79)		x	
13 Aug. (80)		x	
14 Aug. (81)		x	
21 Aug. (88)			x
8 Sept. (106)			x
18 Sept. (116)	x		
25 Sept. (123)			x

† Plots had to be irrigated over several days because the borders were weathered and would not hold 15.2 cm of irrigation water (maximum level of water added) and because rain came during the irrigation periods.

Table 1.3. Rainfall during the growing season of 1980 in Manhattan, Kansas.

Date	Rain
	mm
20 June	14
22 June	15
23 June	3
2 July	2
3 July	14
21 July	11
25 July	3
26 July	2
1 Aug.	1
4 Aug.	5
5 Aug.	2
10 Aug.	4
15 Aug.	30
16 Aug.	7
18 Aug.	1
22 Aug.	1
1 Sept.	21
14 Sept.	7
15 Sept.	3
30 Sept.	4
15 Oct.	39
16 Oct.	22
24 Oct.	12
30 Oct.	1
14 Nov.	3

Table 1.4. Rainfall during the growing season of 1981 in Manhattan, Kansas.

Date	Rain
	mm
1 May	2
5 May	21
8 May	10
9 May	42
12 May	5
13 May	1
14 May	4
18 May	48
19 May	13
25 May	20
29 May	8
2 June	3
5 June	4
11 June	25
15 June	30
21 June	23
22 June	1
26 June	14
28 June	47
2 July	5
3 July	15
4 July	2
9 July	56
15 July	2
17 July	2
18 July	21
19 July	2
20 July	37
22 July	3
27 July	65
3 Aug.	42
5 Aug.	11
7 Aug.	9
10 Aug.	27
14 Aug.	8
26 Aug.	5
28 Aug.	2
1 Sept.	15
24 Sept.	12

Table 1.5. Temperature on days measurements were taken in 1980.

Date	Maximum temperature	Minimum temperature
	°C	
12 June	32	21
17 June	28	13
27 June	34	14
1 July	40	27
8 July	40	28
22 July	31	17
28 July	41	19
1 Aug.	41	24
6 Aug.	36	21
20 Aug.	33	27
26 Aug.	39	21
2 Sept.	34	17
6 Sept.	37	22

Table 1.6. Temperature on days measurements were taken in 1981.

Date	Maximum temperature	Minimum temperature
	°C	
14 May	21	9
9 June	36	24
17 June	29	16
18 June	26	19
19 June	29	16
25 June	29	22
13 July	36	27
16 July	32	24
23 July	31	22
31 July	31	22
3 Aug.	32	22
18 Aug.	24	13
17 Sept.	17	6

Table 1.7. Effect of irrigation water on canopy minus air temperature (T_c − T_a) of alfalfa in 1980.

Irrigation water	Harvest date: 8 July†	6 Aug.†	6 Sept.‡
cm	°C		
0.0	-2.7a	+1.4a	-1.0a
2.5	-4.3ab	-0.8ab	-1.6ab
5.1	-4.7ab	-3.0bc	-2.7bc
7.6	-5.7b	-3.9c	-3.4c
10.2	-5.7b	-4.1c	-3.5c
12.7	-5.8b	-4.2c	-3.6c
15.2	-5.7b	-5.0c	-3.8c

† Each value is the mean of 12 to 19 replications in a treatment averaged over the entire growth period. Means in each column that have the same letter are not significantly different. A regression approach and Duncan's multiple range test were used at the 0.05 level of significance. In this table and all other tables in the thesis with statistical tests, the following procedures were used. A lower limit of acceptable P>F (α level) was chosen to be 0.25 or a 75% chance that treatment means were not equal. If the level went lower than this value, then there was no significant difference among the treatment means. In other words, if there were up to a 75% or greater chance that the treatment means were different, Duncan's test at the 0.05 level of significance was then used to test for differences among treatment means. Dunnett's test, Newman-Keul's test, and Tukey's test were also run; and usually the results were the same as those obtained with Duncan's test. All these tests are described by Zar (1974).

‡ Each value is the mean of 24 to 29 replications in treatment. On some dates, only one measurement per treatment was taken (see text). Data were analyzed using the same method outlined above.

Table 1.8. Effect of irrigation water on canopy minus air temperature (T_c - T_a) of alfalfa in 1981.

Irrigation water	Harvest date			
	26 May†	6 July†	9 Aug.†	18 Sept.‡
cm	°C			
0.0	+2.2a	-4.4a	-4.0a	-2.1a
2.5	+2.1a	-4.4a	-4.1a	-2.2a
5.1	+2.0a	-4.7a	-4.2a	-2.3a
7.6	+1.5a	-4.7a	-4.3a	-2.3a
10.2	+1.3a	-4.7a	-4.3a	-2.3a
12.7	+1.3a	-4.8a	-4.3a	-2.3a
15.2	+1.2a	-4.9a	-4.3a	-2.5a

† Each value is the mean of 6 to 24 replications in a treatment averaged over the entire growth period. See first footnote of Table 1.7 for meaning of letters in the table.

‡ See second footnote of Table 1.7.

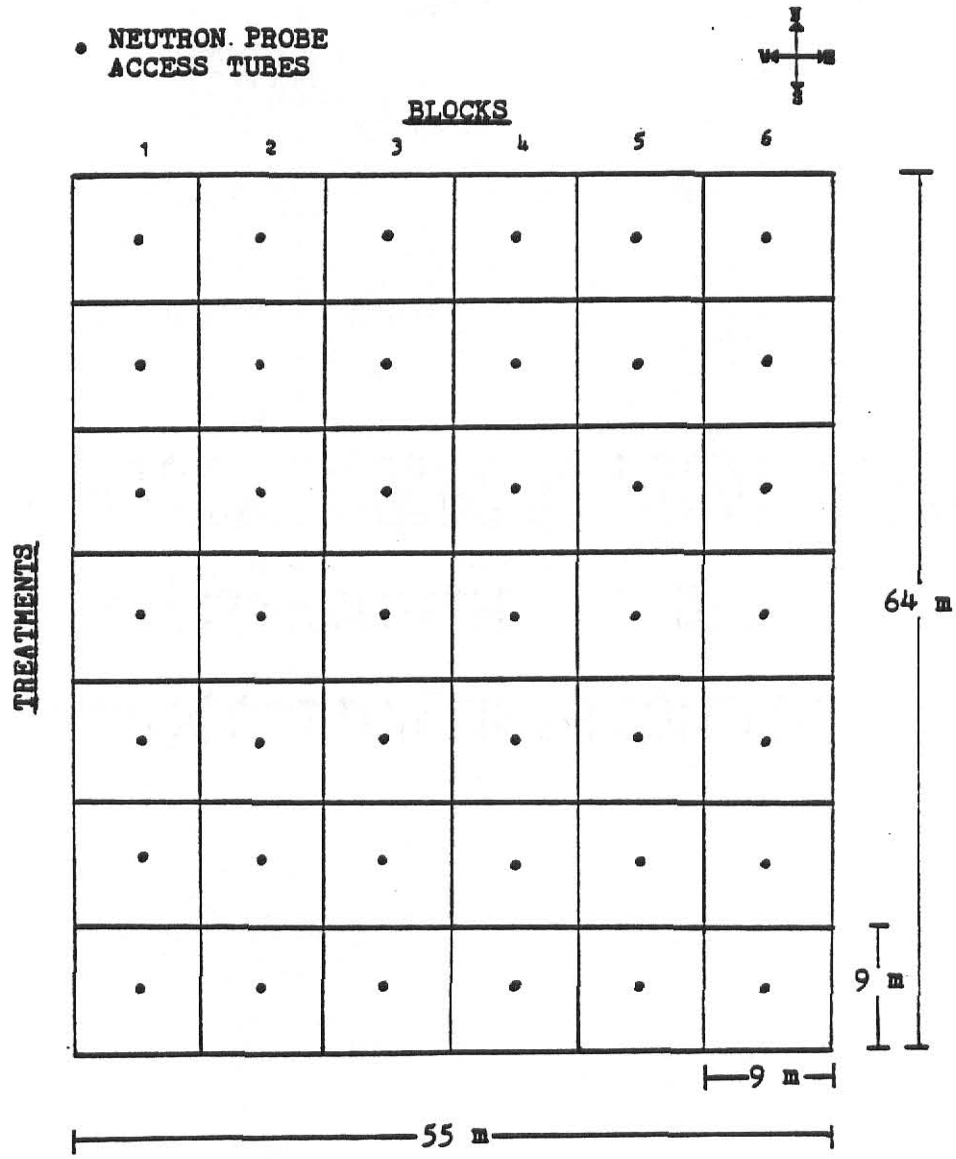

Fig. 1.1. Experimental design. Randomized complete block, with six blocks and seven treatments randomized within each block. Plots were numbered consecutively, E to W, then W to E, etc., beginning in the SE corner and ending in the NW corner.

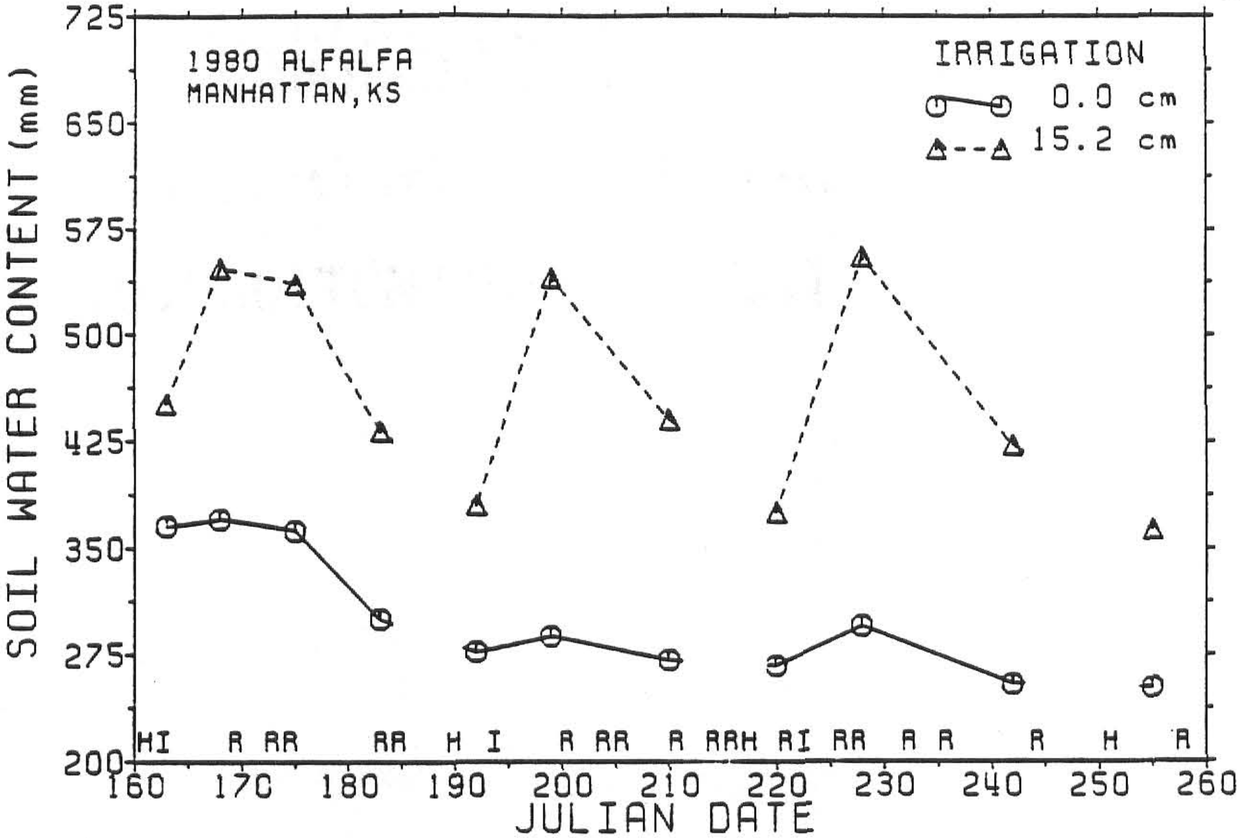

Fig. 1.2. Soil water content (3.2 m Profile) over time (growin season) in 1980. Abbreviations: harvest (H), irrigation (I), and rain (R).

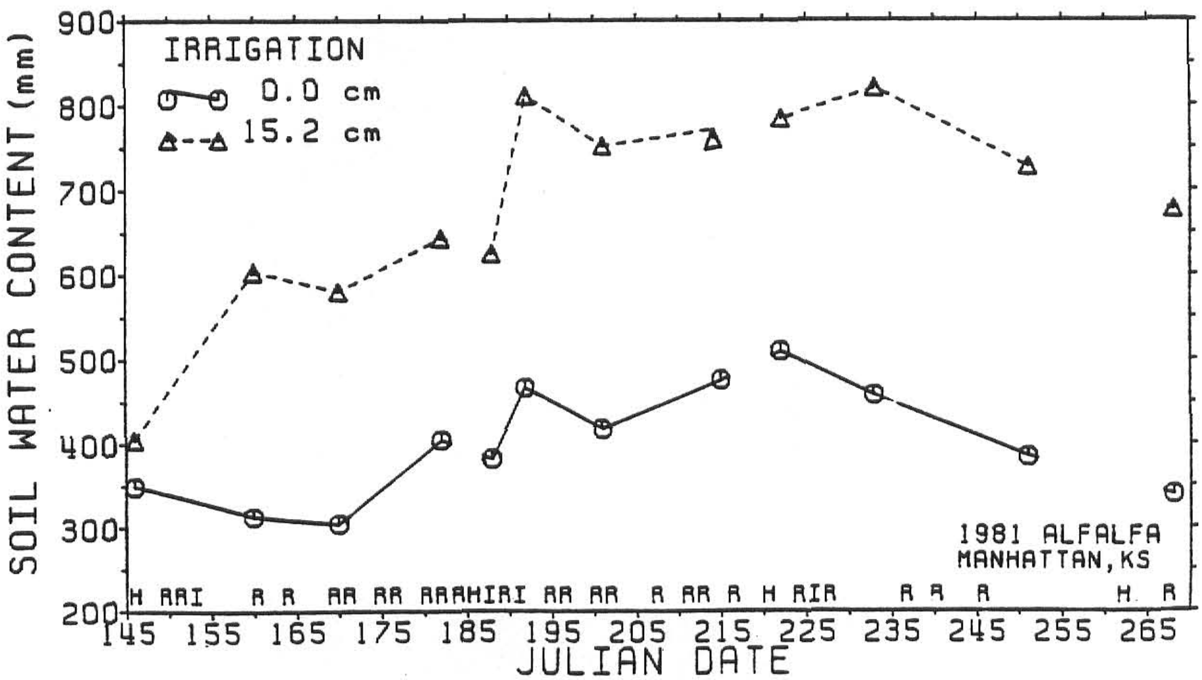

Fig. 1.3. Soil water content (3.2 m profile) over time (growing season) in 1981. For abbreviations, see legend of Fig. 1.2.

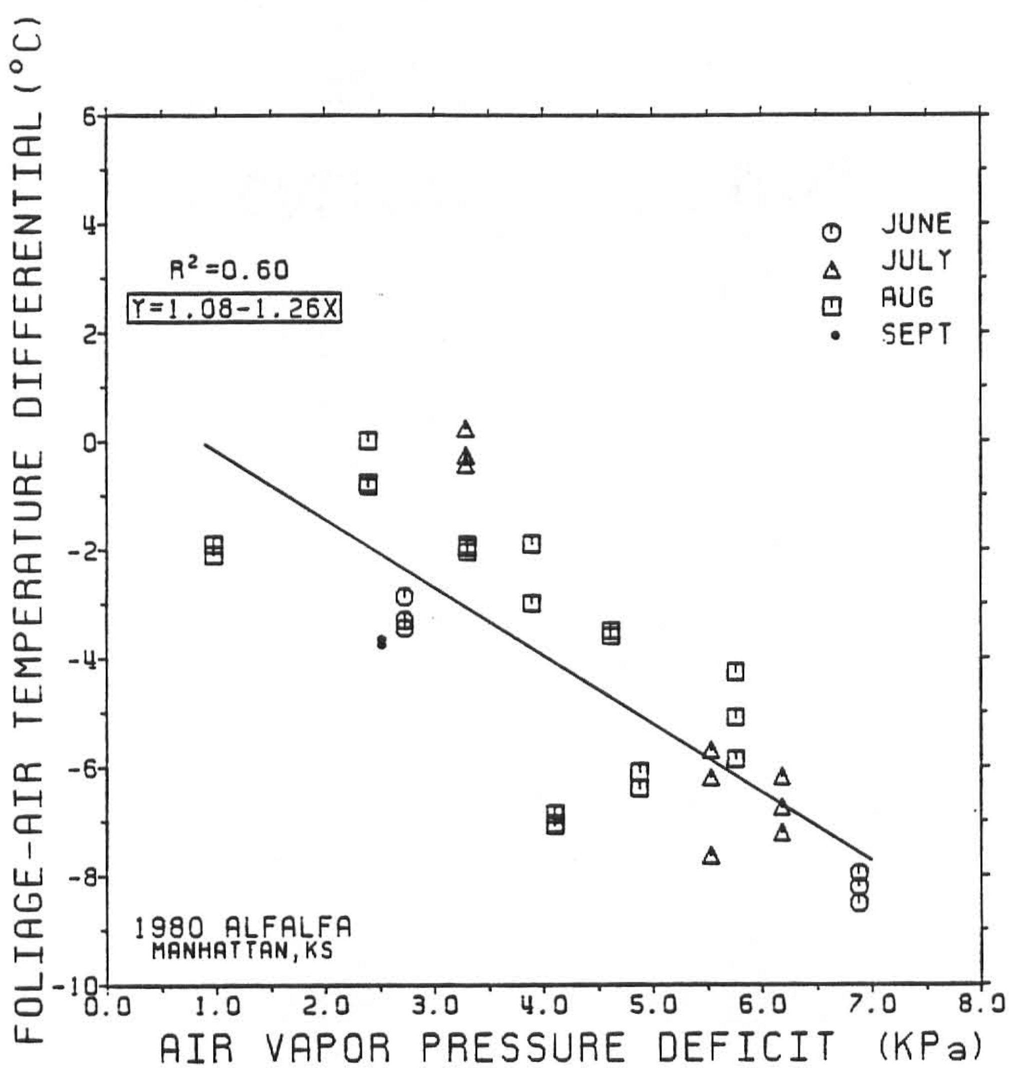

Fig. 1.4. Foliage-air temperature differential versus vapor pressure deficit of well-watered (10.2, 12.7, and 15.2 cm regimes only) alfalfa in 1980.

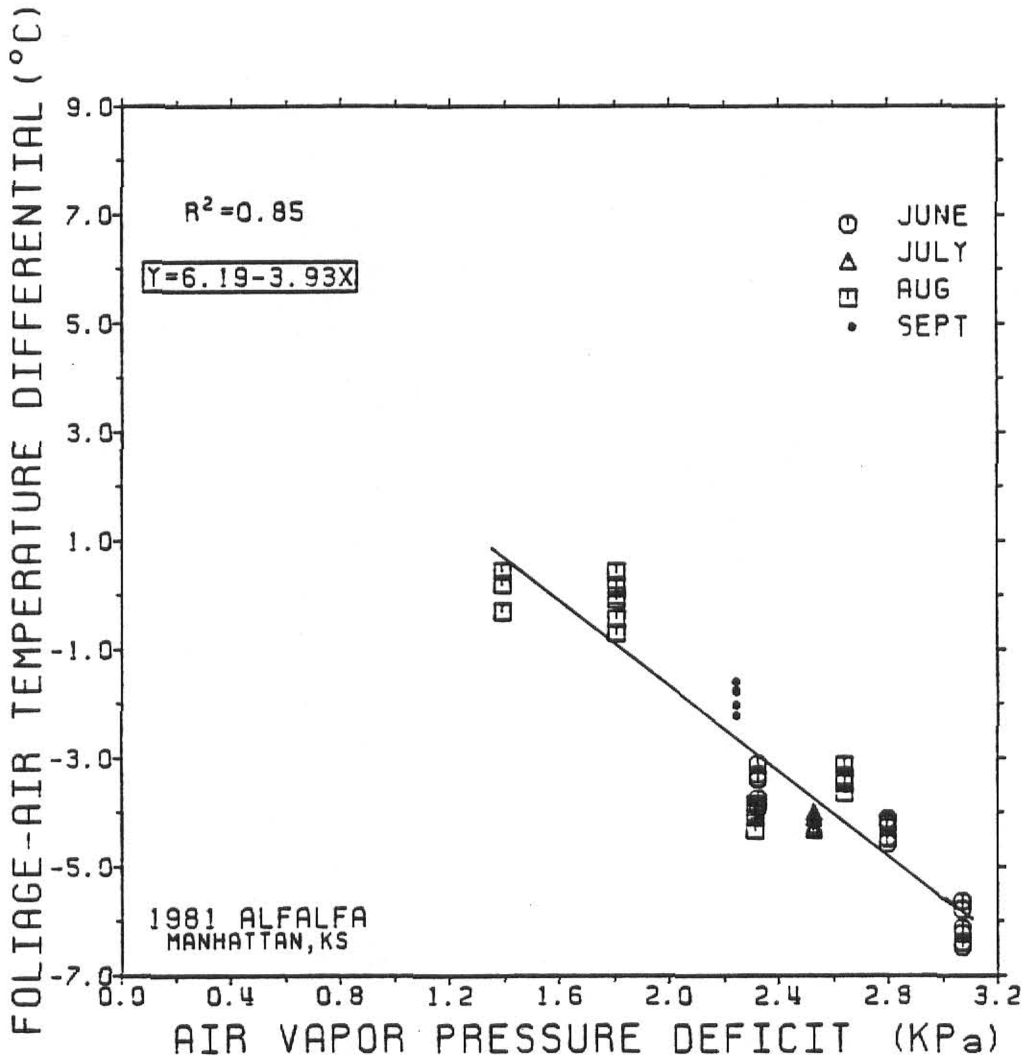

Fig. 1.5. Foliage-air temperature differential versus vapor pressure deficit of alfalfa in 1981. All seven levels of irrigation were used in the analysis.

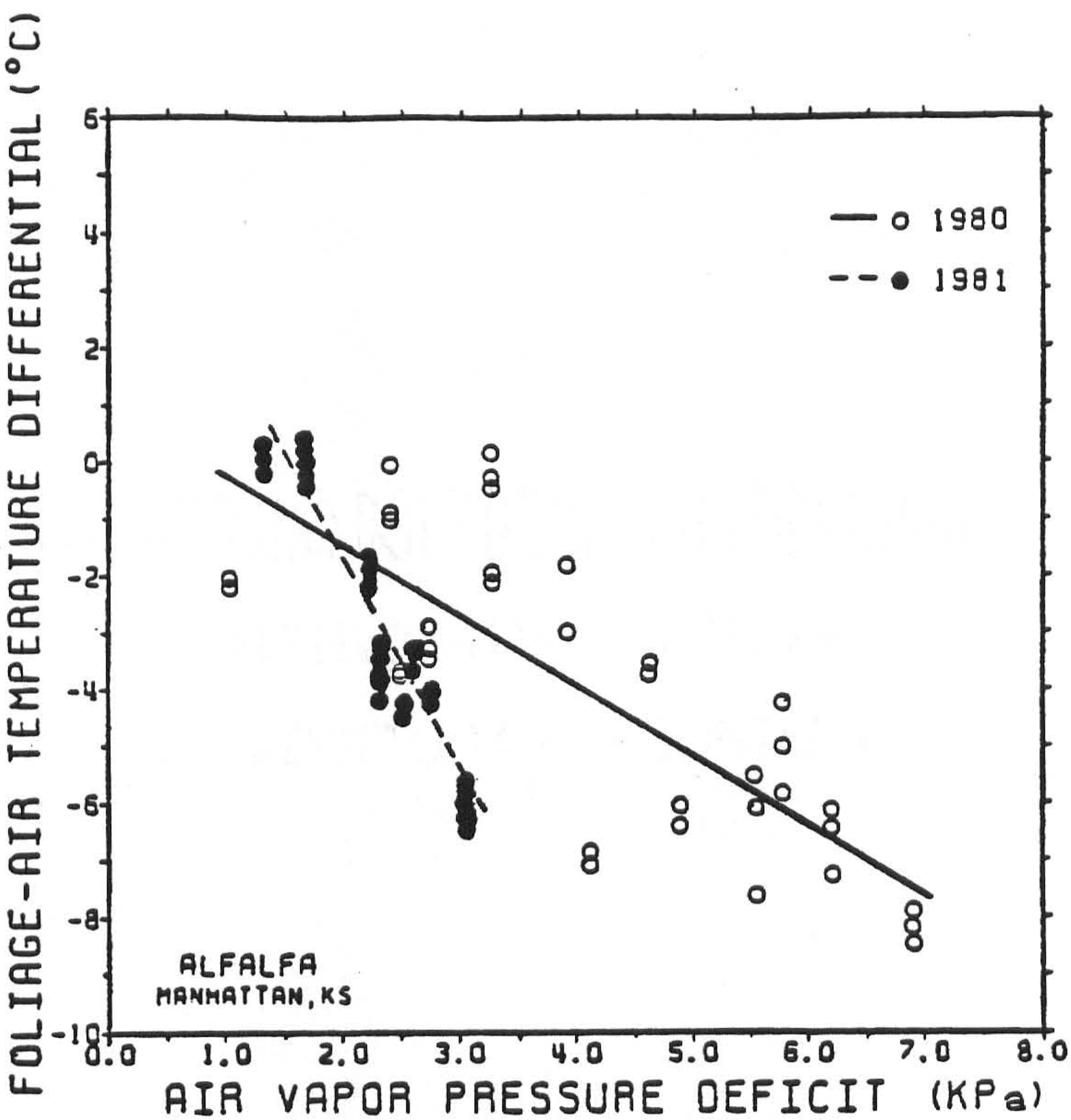

Fig. 1.6. Foliage-air temperature differential versus vapor pressure deficit of well-watered alfalfa in 1980 and 1981 (combination of Figs. 1.4 and 1.5).

CHAPTER 2

ASSESSMENT OF THE GROWTH OF ALFALFA FROM SPECTRAL REFLECTANCE MEASUREMENTS

ABSTRACT

Alfalfa (*Medicago sativa* L. 'Cody') was grown under seven watering regimes to determine the effect of water on growth of alfalfa in the Southern Great Plains. Irrigation water (0, 2.5, 5.1, 7.6, 10.2, 12.7, or 15.2 cm) was added after each of three harvests in both 1980 and 1981. Throughout the growth period in both years, leaf area, stem dry weight (SDW), leaf dry weight (LDW), soil moisture, and reflectance were measured. Soil moisture, leaf area, and reflectance were determined using, respectively, a neutron-attenuation probe, an optical scanning meter, and a hand-held radiometer. Yield was determined at harvests in July, August, September, and November of 1980, and May, June, July, August, and September of 1981. Contrasts in weather between the two summers enabled comparison of data from a year with water deficit (1980) to those of a wet year (1981). Rainfed plants (dryland) in 1980 usually had the lowest yield, and plants irrigated with 5.1, 7.6, 10.2, 12.7, 15.2 cm water generally had significantly higher yield than plants grown dryland. In 1981, rainfed plants showed no difference in yield compared with irrigated plants. The ratio of LDW to total dry weight was about 0.5, and this ratio remained relatively constant between irrigation treatments and years.

Leaf-area index (LAI) was related to total dry weight and growing-degree days using a multiple-regression equation. The equation seemed to describe adequately the data for both years, but requires further validation. A vegetative index (VI), obtained by calculating a ratio of the difference of thematic mapper bands TM4 (0.76 to 0.90 µm) and TM3 (0.63 to 0.69 µm) [(TM4 − TM3)/(TM4 + TM3)] was directly related to leaf-area index. Dryland plants had the lowest VI in 1980, but differences among irrigation treatments were not evident. In 1981, there was no significant difference between VI of irrigated plants and dryland plants.

INTRODUCTION

In the Southern Great Plains, alfalfa is irrigated because rainfall is sporadic and amounts are often low. Alfalfa usually develops an extensive root system, particularly on deep soils. It is relatively drought tolerant and vegetative yield is mainly dependent on available water (Vough and Marten, 1971; Jung and Larson, 1972). Studies on irrigated alfalfa have been carried out in Arizona, (Dorbrenz et al., 1971), California (Hagemann et al., 1978), Nebraska (Daigger et al., 1970), and New York (Lucey and Tesar, 1965). No experiments have been done in the Southern Great Plains, where new varieties of alfalfa are being released at an unprecedented rate (Reinhardt et al., 1978; Shroyer et al., 1981). The drought, high temperatures, and desiccating winds of the area make a unique set of climatic hazards that can severely limit production.

The growth and development of leaf tissue in forage crops is important from the standpoint of the quantity and quality of the yield. Monitoring of plant growth has traditionally been done by hand, clipping plants from a known area and weighing the vegetation removed to get wet or dry weight per unit area. Leaves occur in various shapes and sizes, and it is difficult to measure the intact leaf area of a plant.

Leaf-area-index (LAI) measurements of alfalfa are particularly tedious because of the numerous small leaves. Robison and and Massengale (1967) found that leaf weight could be used to determine the leaf area of 'Moapa' alfalfa grown in Tucson, Ariz., at various stages of growth or for different seasons of the year. Schreiber et al. (1978) developed and validated a computer model of alfalfa growth, called SIMED, that used weather data to predict the accumulation of dry matter in leaves, stems, and roots.

With the advent of advanced computer technology and data collection, monitoring the development of an intact crop canopy and its biomass are possible by means of remote sensing by satellites (Pollock and Kanemasu, 1979). Many investigators have used hand-held radiometers to measure reflectance from agricultural crops. Tucker et al. (1979) reported that reflectances from corn and soybeans were significantly related to several agronomic variables, including biomass and percent crop cover. Leaf-area index, estimated from multispectral data, can be used in yield models to predict biomass and grain yield (Mohiuddin and Kanemasu, 1982).

Little work has been done to measure the growth and reflectance of alfalfa irrigated with different amounts of water in a subhumid region. The purpose of this study was to determine the effect of differential irrigation on the vegetative yield of alfalfa and assess reflectance measurements as a method of estimating the yield.

MATERIALS AND METHODS

The experiment was conducted during the summers of 1980 and 1981 at a field site located about 3 km (2 miles) southeast of Manhattan, Kansas. The soil type was Eudora silt loam, classified as a Pachic Haplustoll, fine silty, mixed, mesic (Jantz et al., 1975). Alfalfa (*Medicago sativa* L. 'Cody') was planted in 1978 on leveled land and 42 plots each measuring 9 m x 9 m were established (Fig. 1.1). Access tubes for neutron-moderation measurements were placed in the center of each plot to a depth of 3.5 m (one tube per plot). Borders of soil enclosed the plots and gated irrigation pipe (20 cm diameter) was set on top of the borders. The experimental area was surrounded by 6 m of 'Cody' alfalfa. The plots were irrigated with 0, 2.5, 5.1, 7.6, 10.2, 12.7, or 15.2 cm of ground water (six replications of each amount) at three different times during each of the two growing seasons (Tables 2.1 and 2.2). The experimental design was a randomized complete block. There were seven water treatments (six levels of irrigation; one dryland) in each of six blocks (six replications). The irrigation levels were gauged using meter sticks to measure the depth of irrigation water received, while the water was being rapidly released through the gated pipe. The alfalfa surrounding the experimental area was soaked with water (amount added not measured) on the dates of irrigation.

In 1980, irrigation water and stored soil water were the main sources of water for the plants because the summer was dry. This contrasted with the summer of 1981, which was wet (Tables 1.3 to 1.6). The National Oceanic and Atmospheric Administration (1980, 1981) characterized June and July of 1980 as one of the "driest" periods on record with "torrid" heat, and June and July of 1981 as having very heavy producing large rainfall totals. The extremes in weather between the summers of 1980 and 1981 enabled comparison of data from a stressed season with those from a non-stressed season.

Throughout the growth period, soil moisture, leaf area, dry weight, and reflectance were measured. Tables 2.1 and 2.2 show the dates measurements were taken in 1980 and 1981, respectively. Soil-water status was determined at seven-to-ten-day intervals with a neutron-attenuation probe. The readings were taken to a depth of 3.2 m, in each of the 42 plots. Depth increment for the probe measurements was 15.2 cm. Fifteen-second-standard counts were taken before and after reading each tube. Total water in the 3.2 m soil profile was determined by adding together the amount of water in each layer (15.2 cm increment) of soil.

Leaf area was measured using an optical scanning meter (Model LI-3100, Li-Cor, Inc., Lincoln, Neb.). At least one, and sometimes two, plant samples from each irrigation treatment were taken from a 20.3 cm x 20.3 cm area of ground. After leaf area was measured, the individual leaves and stems from each sample were oven-dried (60 to 70°C) and weighed.

Reflectance was monitored with a hand-held radiometer, which was configured spectrally to thematic mapper bands TM3 (0.63 to 0.69 µm), TM4 (0.76 to 0.90 µm) and TM5 (1.55 to 1.75 µm). These three bands are sensitive to the cholorophyll density, the green-leaf density, and the leaf-water density, respectively (Tucker et al., 1981). In this study, only the red (0.63 to 0.69 µm) and one infrared (IR) (0.76 to 0.90 µm) bands were used, because the third band (TM5) has been shown to give unreliable results. Reflectance values were determined by using a highly reflective barium-sulfate panel as a reference. A dark-level response of the instrument was obtained by holding an opaque surface over the optical ports, to check for system noise or deviation from zero. The response of the reference was measured about every 15 minutes during the time data were collected, and the dark-level response was measured every 40 minutes. Three duplicate observations were taken for each plot and were averaged for analysis. Data for reflectance were acquired away from the plant-sampling area, to make sure that the plants viewed by the radiometer were intact. Data were gathered between 12:00 and 15:00 CDT, when the angle of the sun was greater than 45 degrees above the horizon (Jackson et al., 1980). When weather permitted, radiometer readings were taken at the same time that plant samples were taken.

The reflectance data were used to calculate a normalized vegetative index VI), as follows:

$$VI = \frac{(IR - RED)}{(IR + RED)} = \frac{(TM4 - TM3)}{(TM4 + TM3)}$$

where IR (TM4) and RED (TM3) are reflectance values (Jackson et al., 1980).

In the regression model relating leaf-area index to total dry weight (TOTDW) (i.e., leaf + stem dry weight in kg/m^2), growing-degree days (GDD) was used as one of the independent variables with a threshold temperature of $5^{o}C$ and the formula (Lowry, 1969; Schreiber et al., 1978):

$$GDD = \sum_{i=1}^{H} \left[\left(\frac{T_{max} + T_{min}}{2} \right) - 5 \right]$$

in which

T_{max} = maximum daily temperature; if it were greater than $30^{o}C$, it was reset to $30^{o}C$.

T_{min} = minimum daily temperature; if it were less than $5^{o}C$, it was reset to $5^{o}C$.

H = end of the growth period (harvest date).

The 1981 data were used to test the aptness of the 1980 regression model (Splinter, 1974; Loomis et al., 1979). The following constraints were imposed on the 1981 data before analysis to avoid erroneous extrapolation from the 1980 regression equation:

$$0.027 \geq \text{TOTDW}(kg/m^2) \leq 0.450$$

$$87 \geq \text{GDD} \leq 438$$

$$0.2 \geq \text{LAI} \leq 5.7$$

Statistical methods used to test the regression model were extra-sum-of-squares and likelihood-ratio tests (Neter and Wasserman, 1974; Helwig and Council, 1979, p. 255).

The regression models relating normalized vegetative index to leaf-area index and total dry weight were analyzed using the modified Gauss-Newton-iterative-non-linear-estimation method (Olinick, 1978; Helwig and Council, 1979, p.317-329; Snedcor and Cochran, 1980, p. 393-413). This method was used because the data do not need to be mathematically transformed, and they may be used directly in the equation. Each set of measurements (i.e., not means) of VI from each plot were equated with the respective LAI and TOTDW before analysis.

Vegetative indices determined for an entire growth period, from all 42 plots, were investigated using a regression approach to analysis of variance (RANOVA). Data examined using RANOVA, or other types of analyses, are noted below the tables.

RESULTS AND DISCUSSION

Weather during the summers of 1980 and 1981 was different. Tables 1.3 to 1.6 show the rainfall and temperature data for 1980 and 1981. In 1980, temperature was generally extremely hot, and the amounts of rain were low. Temperature in 1981 was cooler, and the rainfall for the summer was three times as much as it was in 1980. The main sources of water for alfalfa grown during the droughty year of 1980 were stored soil water and applied irrigation water. Figures 1.2 and 1.3 show the soil-water content of irrigated (15.2 cm) and dryland alfalfa grown in 1980 and 1981, respectively. The differences in weather between 1980 and 1981 permitted investigation into the growth of irrigated and non-irrigated alfalfa subjected to arid conditions in 1980 and wet conditions in 1981.

Tables 2.3 and 2.4 show the effect of irrigation on the yield of alfalfa grown during the dry year of 1980 and the wet year of 1981, respectively. In 1980, rainfed plants usually had significantly lower yields than the irrigated plants (Table 2.3). Plants irrigated with 15.2 cm of water generally had the highest yield, even though yield was not statistically different from plants receiving 5.1, 7.6, 10.2, or 12.7 cm of irrigation water. In the second harvest (6

August 1980), there was a reduction in yield compared with the first harvest and then a slight increase in yield in the third harvest (8 September 1980). Improvement in yield observed in the September harvest indicated that the stand was probably recovering from previous heat stress.

Decline in growth of alfalfa during the hot weather of summer, commonly referred to as "summer slump," is generally experienced in the southwestern United States (Bula and Massengale, 1972). Above-optimal temperatures (>30^{o}C) may persist for extended periods and induce stress. Alfalfa, grown at high temperature and soil-moisture stress, maintains vegetative growth for shorter periods and yields less dry matter than alfalfa grown at a lower temperature and with no soil-moisture stress (Vough and Marten, 1971). Pulgar and Laude (1974) observed depression in growth of alfalfa following heat stress. Decreased yield at the November harvest of 1980 (Table 2.3) was attributed to below-optimal temperatures (<5^{o}C) associated with the fall season. The reduction in yield of non-irrigated alfalfa, compared to that of irrigated plants, suggested that irrigation during dry conditions, such as the 1980 growing season in Kansas, was important for forage production.

In 1981, yields of plants grown dryland were usually similar to those of plants grown with irrigation water (Table 2.4). This suggested that the crop-water requirement was adequately supplied by rainfall and water stored in the soil profile.

Leaf dry weight (LDW) and stem dry weight (SDW) were examined in both years to establish if differences in weight existed among the treatments. Figures 2.1 and 2.2 show the partition of average LDW (g/m^2) and SDW (g/m^2) components of total dry weight (TOTDW) (i.e., LDW + SDW) of samples taken in 1980 and 1981, respectively. The TOTDW appeared to agree with the samples taken to determine yield (Tables 2.3 and 2.4). That is, the non-irrigated treatment in 1980 usually yielded less than the irrigated treatments, and there was no difference between treatments in 1981. The proportion of LDW to TOTDW, shown in Figures 2.1 and 2.2, appeared to remain relatively constant for both years and for all growth periods and irrigation treatments. Tables 2.5 and 2.6 show the effect of irrigation on the ratio of LDW to TOTDW for 1980 and 1981. The values indicate that there was no significant difference between the amount of irrigation water applied and the ratio of SDW to TOTDW. This ratio appeared to remain constant for both years. Because the analysis of variance (ANOVA) showed no treatment effect in either year, a regression equation relating LDW to SDW was obtained. The equations were:

1980: $LDW = 11.26 + 0.85SDW$, $R^2 = 0.92$

1981: $LDW = 54.71 + 0.46SDW$, $R^2 = 0.67$

Solving the equations simultaneously for LDW and SDW, adding the results to get TOTDW, and then dividing LDW by TOTDW, one gets the ratio of LDW/TOTDW = 0.49. These equations, solved for their intersection point, and the ANOVA suggested that the ratio of LDW to TOTDW was about one-half, and did not vary significantly among irrigation regimes and appeared to be consistent between years. The TOTDW, LDW, and SDW, viewed individually (i.e., no ratios), however, were usually greater in the cooler and wetter year of 1981 than in the hotter and drier year of 1980.

Figures 2.3 and 2.4 show leaf-area index (LAI) during the summers of 1980 and 1981, respectively. Leaf-area index of alfalfa grown dryland in 1980 was usually lower than that of irrigated alfalfa. Plants grown with 15.2 cm of irrigation water generally maintained the highest LAI (Fig. 2.3). Alfalfa grown in 1981 appeared to have about same LAI for all irrigation treatments (Fig. 2.4). Leaf-area index was directly related to TOTDW (kg/m^2) and growing-degree days (GDD), defined in the Materials and Methods section, using a using a multiple-regression technique. The equations were:

$$1980: \quad LAI = -1.61 + 12.57TOTDW + 0.02GDD - 3.36 \times 10^{-5}GDD^2, \quad R^2 = 0.92$$

$$1981: \quad LAI = -0.69 + 10.44TOTDW + 0.01GDD - 2.44 \times 10^{-5}GDD^2, \quad R^2 = 0.88.$$

All parameters estimated, in both regression models, were significant at greater than the 0.1 level. Standard error of estimate for the parameters were between 7.46×10^{-6} to 0.39. The 1980 and 1981 data were combined into one set of data to test the 1980 equation using the 1981 data (extra-sum-of-squares test). The combined-data-set equation was:

$$\text{CMBEQ:}\quad LAI = -1.40 + 12.1TOTDW + 0.02GDD - 3.21 \times 10^{-5}\,GDD^2,\quad R^2 = 0.92.$$

The 1980 regression model was rejected at greater than the 0.01 level of significance. Further analysis (i.e., likelihood test) was done to compare the differences between the slopes of the two equations (1980 and 1981). There was no detectable difference in year, or the interactions between year and GDD or GDD^2, at the 0.05 level of significance. Significant differences were TOTDW, GDD, and GDD^2, and the interaction, TOTDW, and year. These differences suggested that there were deviations in temperature (GDD and GDD^2) and TOTDW between the two years. Schreiber et al. (1978), using a computer model (SIMED) to simulate alfalfa growth, found that solar radiation and temperature were two important environmental factors, which determined alfalfa growth. In sensitivity analyses done with SIMED by Schreiber et al. (1978), growing-degree days and solar radiation were varied to examine the effect on the growth of various plant components and final yield. They found that radiation exerted less influence than temperature on crop-growth rate and that plants at cooler temperatures maintained growth for longer periods of time than those grown at higher temperatures. The statistical tests done two LAI-prediction equations (1980 and 1981) seemed to agree with the results reported by Schreiber et al. (1978). Computer simulations (not shown) done on the CMBEQ indicated that it adequately described both years of data, but no data were available to validate the regression model statistically.

The measurements of reflectance showed the differences in canopy characteristics. For example, as leaf area and biomass increased, there was a progressive decrease in reflectance in the chlorophyll-absorption region (0.63 to 0.69 µm) and an increase in the infrared (0.76 to 0.90 µm) reflectance. Normalized vegetative index (VI) was plotted against time in 1980 and 1981 (Figs. 2.5 and 2.6, respectively). Calculated VI usually increased with time as growth increased. Plants grown dryland in 1980 usually had a lower VI than irrigated plants (Fig. 2.5). In 1980, the differences in spectral response between dryland and irrigated alfalfa probably were due to differences in percent soil cover, LAI, and biomass. Plants grown dryland usually had significantly lower yields (Table 2.3) and VI (Table 2.7) than the irrigated plants.

In 1981, VI was generally the same for all irrigation levels (Fig. 2.6; Table 2.8). Infrared reflectance has been reported to be reduced by different types of stress, including salinity, insects, and disease (Daughtry et al., 1980). Differences in VI observed in the first harvest (26 May) of 1981 were attributed to damage from alfalfa weevil. There were heavy infestations of alfalfa weevil in Kansas in the spring of 1981 (Kansas Insect Newsletter, No. 2, 17

April, 1981, Extension Entomology, Kan. State Univ., Manhattan, Kan.). The experimental area was sprayed with Furadan and none of the later harvests in 1981 was affected by weevils.

Figures 2.7 and 2.8 show VI versus LAI in 1980 and 1981, respectively. The VI saturated at LAI = 2.0. Relationships of LAI and reflectance are reported to be slightly non-linear, especially in the red band (Tucker et al., 1979; Bauer et al., 1981). Studies of other canopies have shown an asymptotic response, with the curve levelling off at leaf-area indices greater than 3 or 4 (Daughtry et al., 1980). A curvilinear regression was done for both years to obtain the following equations:

$$1980: \quad VI = 0.770 - 0.770^{(-1.46 LAI)}, \quad R^2 = 0.51$$

$$1981: \quad VI = 0.874 - 0.874^{(-1.34 LAI)}, \quad R^2 = 0.50$$

The results showed that VI could be used to determine LAI at low LAI's (young canopies), but that it could not be used to discriminate differences in LAI at higher LAI's.

CONCLUSION

When alfalfa was irrigated with different amounts of water (i.e., 0, 2.5, 5.1, 7.6, 10.2, 12.7, or 15.2 cm per irrigation), differences in yield, leaf dry weight (LDW), stem dry weight (SDW), leaf-area index (LAI), and normalized vegetative index (VI), due to irrigation treatments, were evident in a dry year, but not in a wet year. In a dry year, the irrigated plots generally had greater yield, SDW, LDW, LAI, and VI than the dryland plots, but differences due to level of water added were not apparent. Therefore, in the dry year, measurements differentiated between wet and dry plots, but did not usually distinguish due to amount of irrigation water applied to the plots.

In both a wet year and a dry year, the ratio of LDW to total dry weight (TOTDW) was about 0.5, but LDW, SDW, and TOTDW were generally greater in the wet year.

Even though VI did not vary due to irrigation, it did distinguish differences in growth (LAI) up to LAI of about 2.0. The results suggested that agronomic practices, such as irrigation, that result in differences in LAI, biomass, and/or percent-soil cover, could be monitored by remote sensing. Therefore, remote sensing may be useful in large-scale estimation of forage production.

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Table 2.1. Dates of harvest, irrigation, leaf-area, spectral, and neutron-probe measurements in 1980.

Date	Harvest	Irrigation	Leaf-area	Spectral	Neutron probe
3 June	x				
11 June					x
13 June		x			
16 June					x
17 June			x	x	
23 June					x
24 June			x	x	
27 June			x	x	
1 July			x	x	x
8 July	x				
10 July					x
14 July		x			
17 July					x
22 July			x	x	
28 July			x	x	x
1 Aug.			x	x	
6 Aug.	x				
7 Aug.					x
11 Aug.		x			
15 Aug.					x
18 Aug.				x	
20 Aug.				x	
26 Aug.				x	
29 Aug.					x
2 Sept.				x	
6 Sept.	x				
11 Sept.					x
7 Nov.					x
11 Nov.	x				

Table 2.2. Dates of harvest, irrigation, leaf-area, spectral, and neutron-probe measurements in 1981.

Date	Harvest	Irrigation	Leaf-area	Spectral	Neutron probe
26 May	x				x
4 June		x			
5 June		x			
6 June		x			
9 June			x	x	x
17 June			x	x	
18 June			x		
19 June					x
25 June				x	
1 July					x
6 July	x				
8 July		x			x
9 July		x			
10 July		x			
11 July					x
13 July			x	x	
16 July			x		
20 July					x
23 July			x		
31 July			x		
3 Aug.					x
9 Aug.	x				
10 Aug.					x
12 Aug.		x			
13 Aug.		x			
14 Aug.		x			
18 Aug.				x	
21 Aug.					x
25 Aug.				x	
29 Aug.				x	
8 Sept.					x
12 Sept.				x	
18 Sept.	x				
25 Sept.					x

Table 2.3. Effect of irrigation water on the dry weight of alfalfa sampled four times in 1980.

Irrigation water	Harvest date			
	8 July	6 Aug.	8 Sept.	11 Nov.
cm	g/m^2			
0.0	208b†	106b	130c	125a
2.5	260ab	181a	180b	130a
5.1	250ab	195a	209ab	140a
7.6	282a	229a	232a	133a
10.2	269ab	212a	212ab	139a
12.7	283a	205a	241a	112a
15.2	272a	227a	247a	135a

† Each value is an average of the six replications in a treatment. See first footnote of Table 1.7 for explanation of letters in table.

Table 2.4. Effect of irrigation water on the dry weight of alfalfa sampled four times in 1981.

Irrigation water	Harvest date 26 May	6 July	9 Aug.	18 Sept.
cm	g/m^2			
0.0	228a†	315b	351a	296a
2.5	281a	335a	358a	294a
5.1	265a	338a	354a	307a
7.6	238a	336a	348a	301a
10.2	250a	336a	365a	311a
12.7	232a	341a	361a	297a
15.2	274a	346a	360a	308a

† Each value is an average of the six replications in a treatment. See first footnote of Table 1.7 for explanation of letters in table.

Table 2.5. Effect of irrigation water on the partition of leaf dry weight to total dry weight sampled in 1980.

Irrigation water	Growth period: 11 June - 8 July	Growth period: 8 July - 6 Aug.
cm	Leaf dry wt./ Total dry wt. (g/g)	
0.0	0.53a†	0.53a
2.5	0.52a	0.52a
5.1	0.58a	0.45a
7.6	0.50a	0.46a
10.2	0.49a	0.46a
12.7	0.48a	0.42a
15.2	0.48a	0.50a

† Each value is the mean of 3 to 7 samples taken from each treatment during that growth period. See first footnote of Table 1.7 for explanation of letters in table.

Table 2.6. Effect of irrigation water on the partition of leaf dry weight to total dry weight sampled in 1981.

Irrigation water	Growth period: 26 May - 6 July	Growth period: 6 July - 9 Aug.
cm	Leaf dry wt./ Total dry wt. (g/g)	
0.0	0.46a†	0.47a
2.5	0.45a	0.49a
5.1	0.45a	0.48a
7.6	0.45a	0.46a
10.2	0.46a	0.44a
12.7	0.45a	0.50a
15.2	0.47a	0.50a

† Each value is the mean of 3 to 7 samples taken from each treatment during that growth period. See first footnote of Table 1.7 for explanation of letters in table.

Table 2.7. Effect of irrigation water on the normalized vegetative index of alfalfa sampled in 1980.

Irrigation water	Harvest date		
	8 July	6 Aug.	8 Sept.
cm	Normalized vegetative index		
0.0	0.65b†	0.53c	0.62b
2.5	0.72ab	0.65b	0.72a
5.1	0.72ab	0.73a	0.73a
7.6	0.73a	0.74a	0.73a
10.2	0.72ab	0.74a	0.73a
12.7	0.73a	0.75a	0.72a
15.2	0.72ab	0.75a	0.74a

† Each value is a mean of 18 to 24 replications in a treatment averaged over the entire growth period. See first footnote of Table 1.7 for explanation of letters in table.

Table 2.8. Effect of irrigation water on the normalized vegetative index of alfalfa sampled in 1981.

Irrigation water	Harvest date: 26 May	6 July	9 Aug.	18 Sept.
cm	Normalized vegetative index			
0.0	0.80ab†	0.89a	0.81a	0.86a
2.5	0.80b	0.89a	0.82a	0.87a
5.1	0.82ab	0.89a	0.82a	0.87a
7.6	0.82ab	0.89a	0.79a	0.87a
10.2	0.83a	0.89a	0.81a	0.86a
12.7	0.81ab	0.89a	0.81a	0.86a
15.2	0.84a	0.89a	0.79a	0.86a

† Each value is a mean of 18 to 24 replications in a treatment averaged over the entire growth period. See first footnote of Table 1.7 for explanation of letters in table.

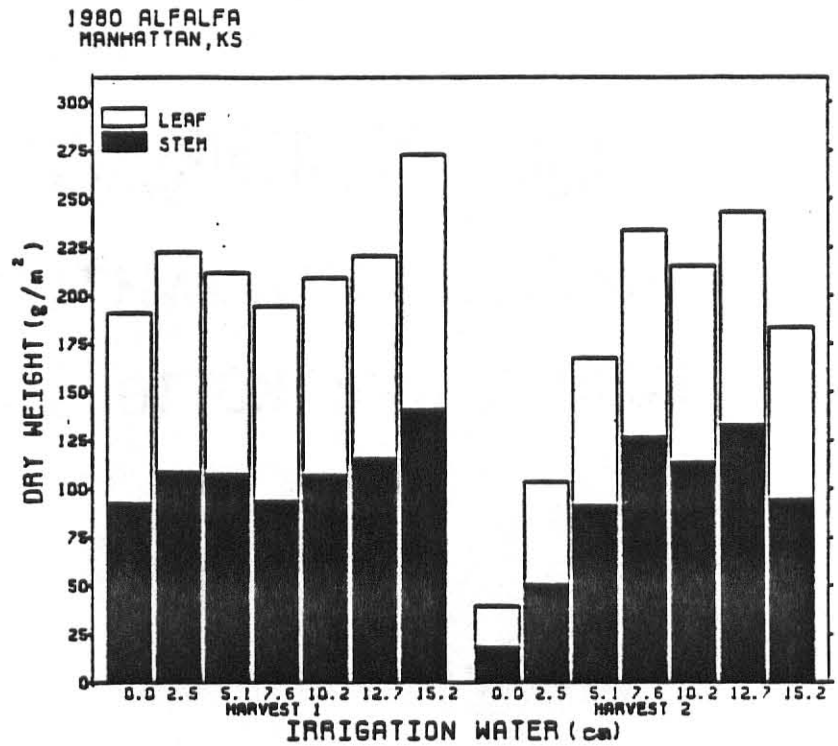

Fig. 2.1. Partition of total dry weight into leaf and stem components using treatment averages, in each of two harvests in 1980.

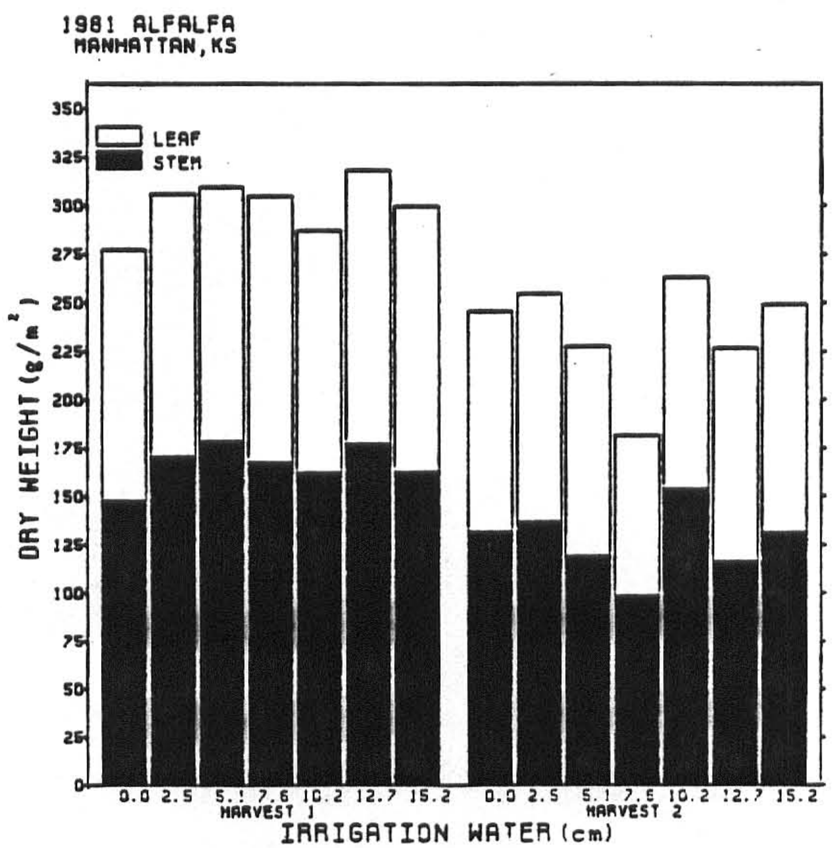

Fig. 2.2. Partition of total dry weight into leaf and stem components using treatment averages, in each of two harvests in 1981.

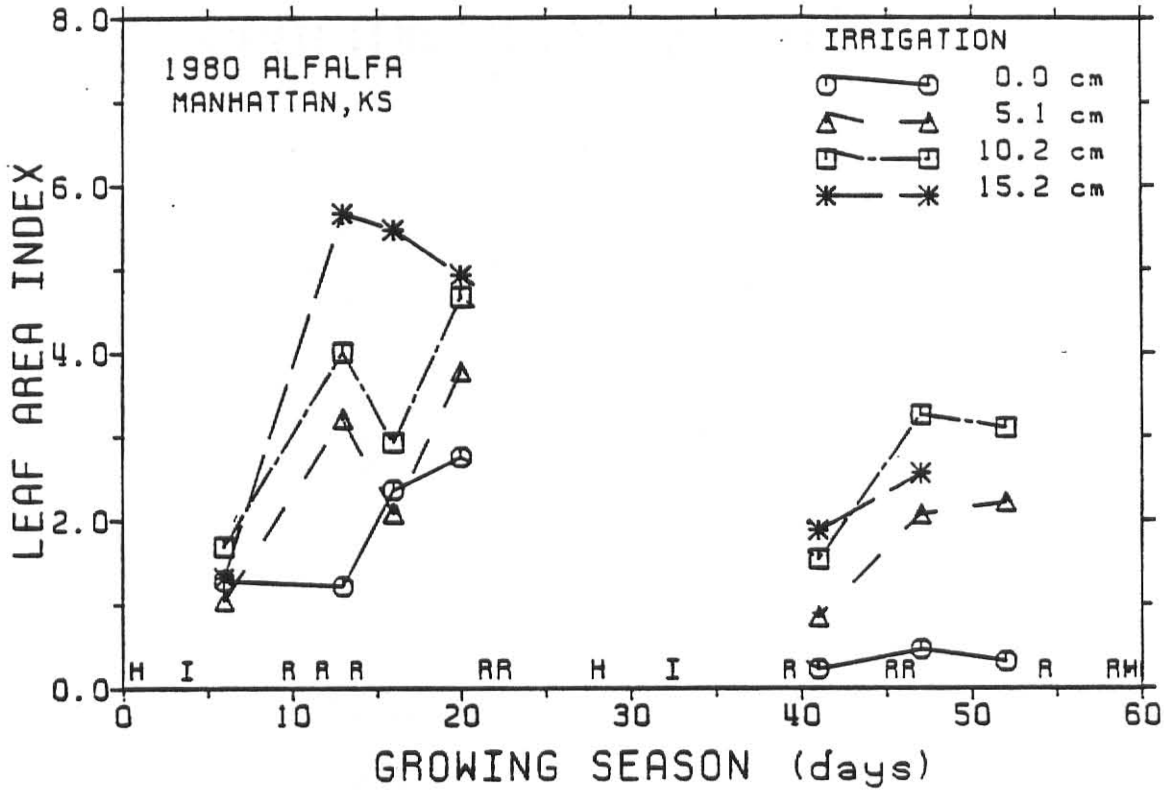

Fig 2.3. Leaf area index over time (growing season) in 1980. Abbreviations: harvest (H), irrigation (I), and rain (R). To make the graph less crowded, only four irrigation regimes are shown.

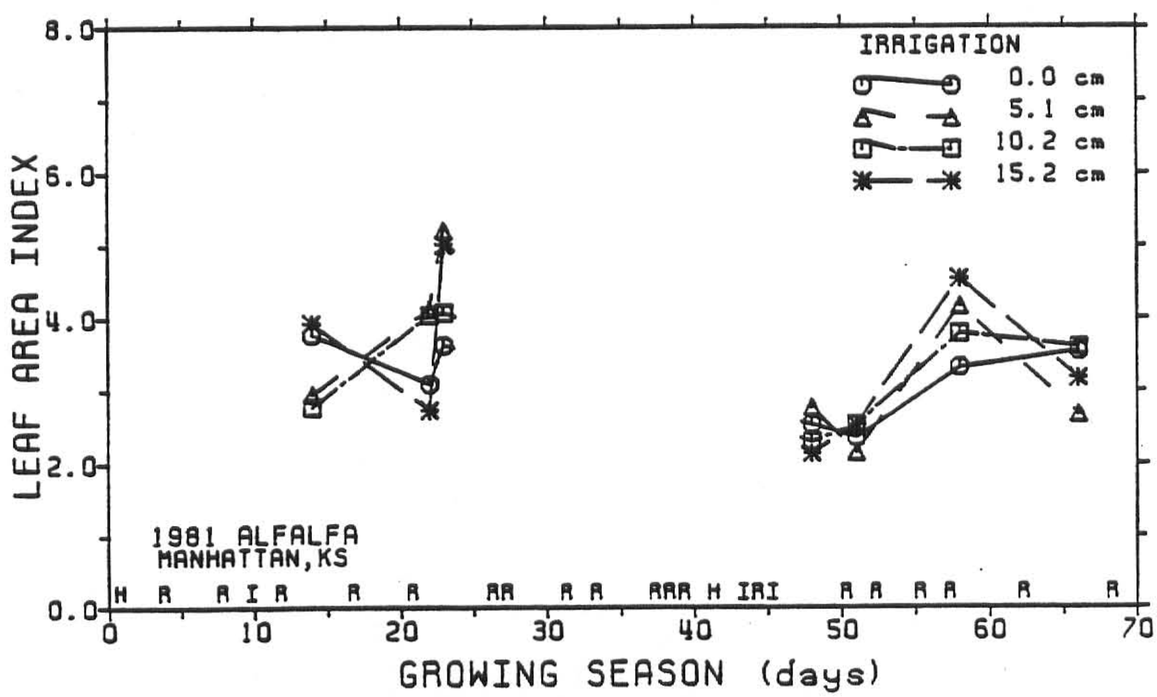

Fig 2.4. Leaf area index over time (growing season) in 1981. For abbreviations, see legend of Fig. 2.3.

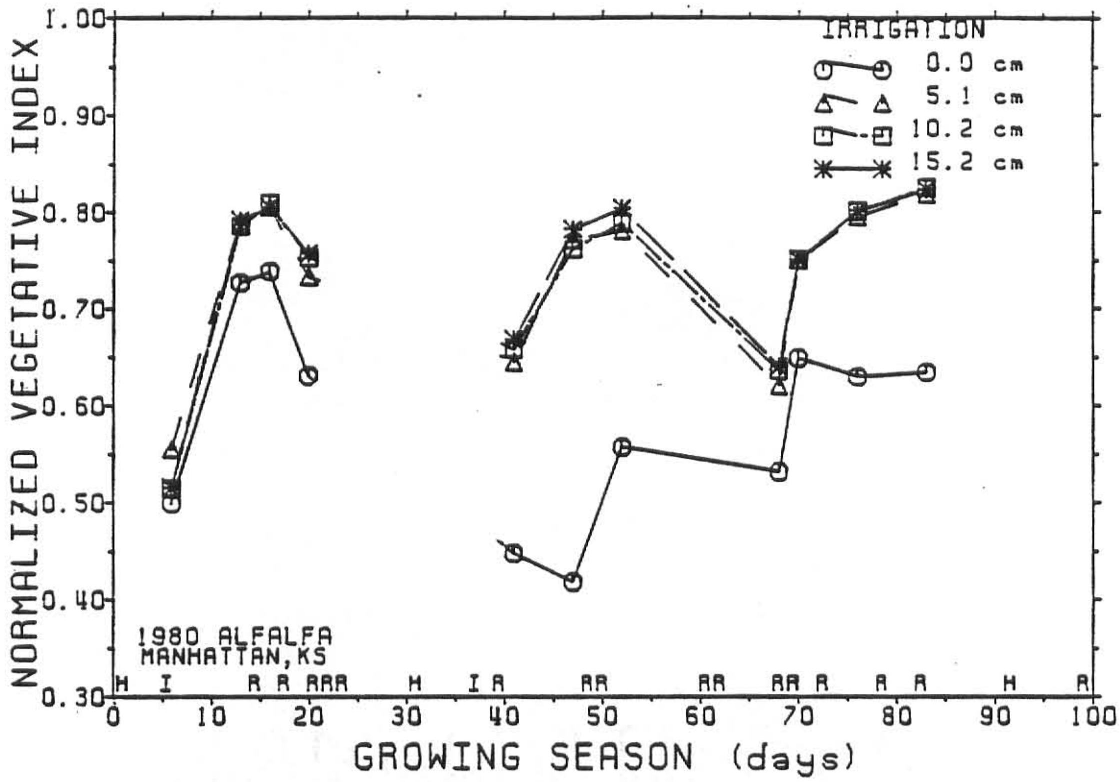

Fig. 2.5. Normalized vegetative index over time (growing season) in 1980. For abbreviations, see legend of Fig. 2.3.

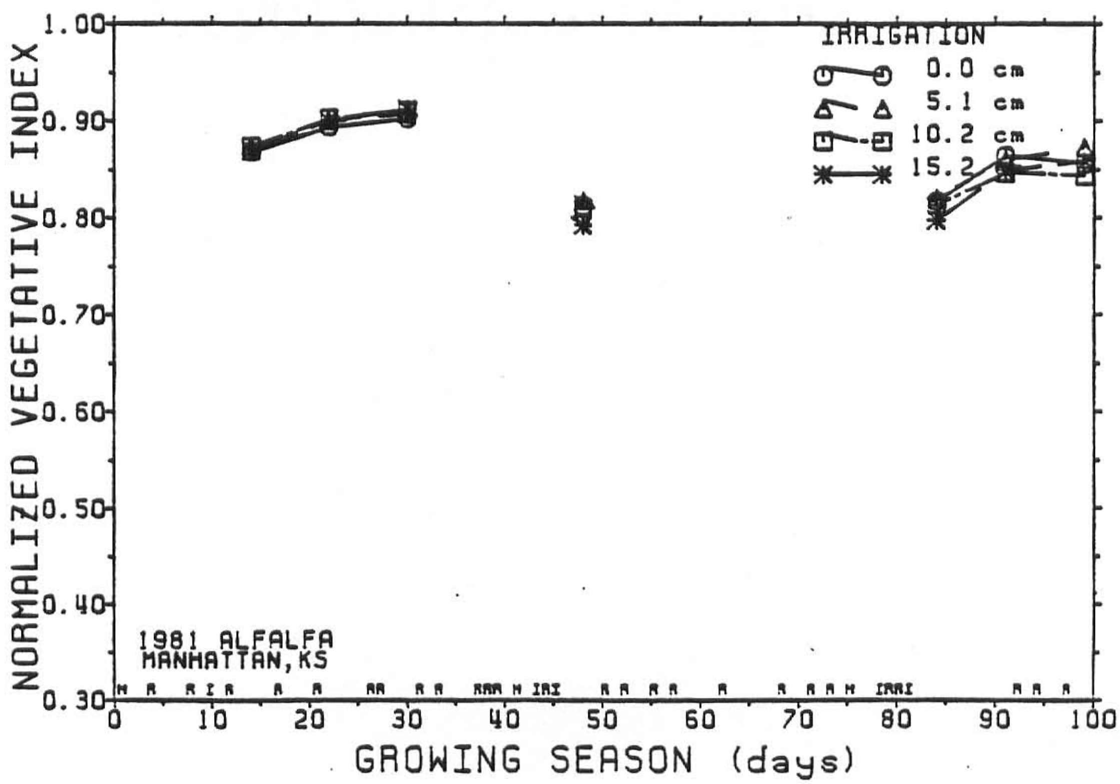

Fig. 2.6. Normalized vegetative index over time (growing season) in 1981. For abbreviations, see legend of Fig. 2.3.

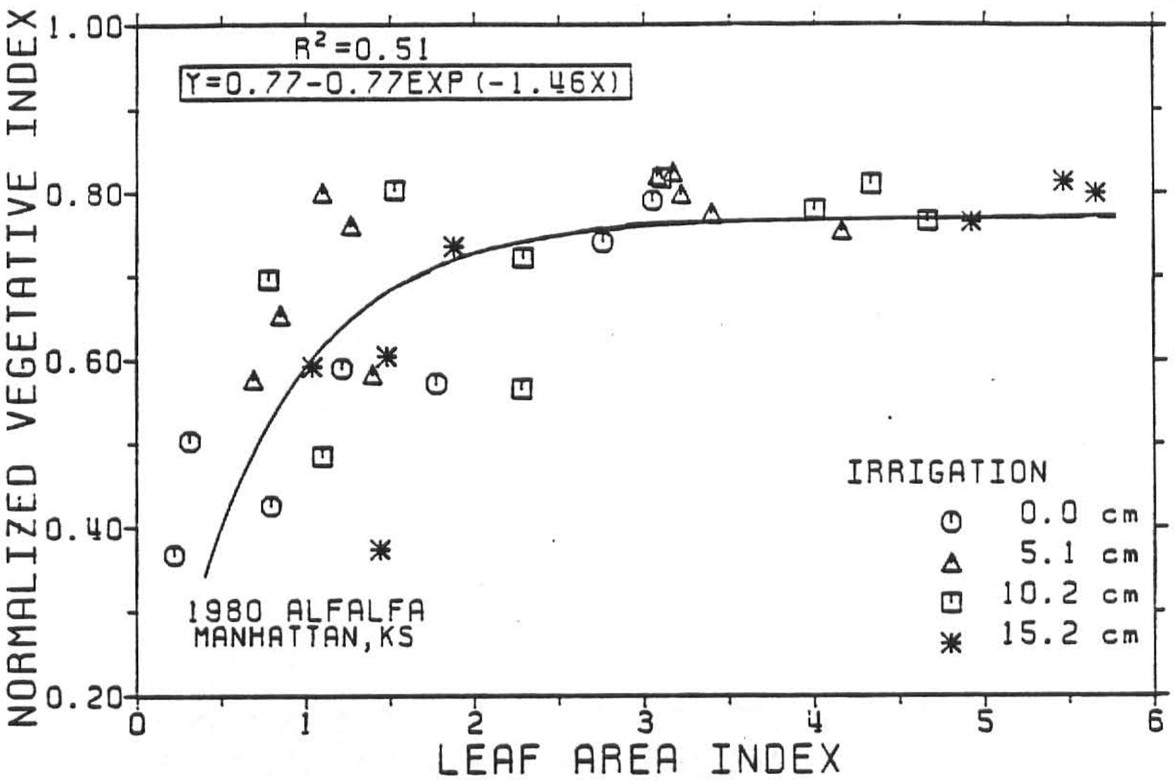

Fig. 2.7. Asymptotic relationship of normalized vegetative index and leaf area index of all irrigation treatments (subset of regimes shown to simplify graph) in 1980.

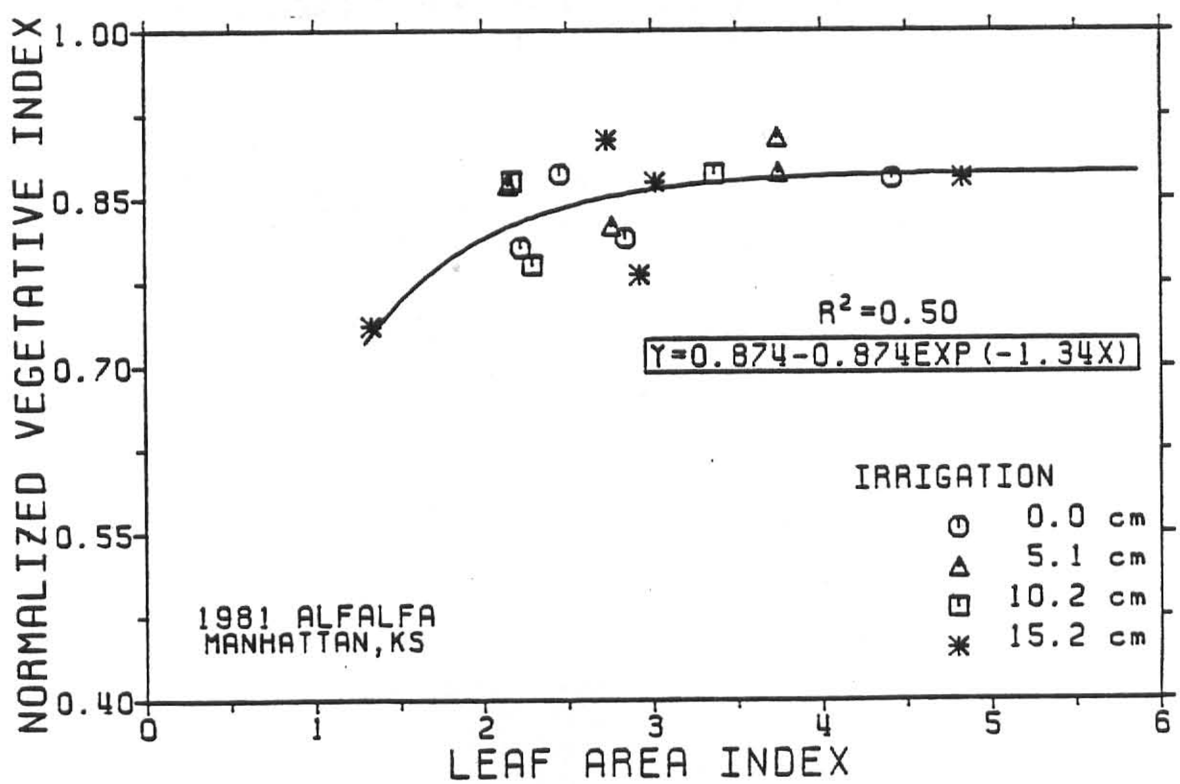

Fig. 2.8. Asymptotic relationship of normalized vegetative index and leaf area index of all irrigation treatments (subset of regimes shown to simplify graph) in 1981.

APPENDIX A

GLOSSARY OF TERMS

USED IN APPENDIX A

ANOVA	Analysis of variance
AVGTDIFF	Average canopy minus air temperature differential of the seven treatments (^{o}C)
C. V.	Coefficient of variation (C. V.= σ/μ)
GDD	Growing degree days
GDD2	Growing degree days squared (i.e., GDD^2)
LAI	Leaf area index
R^2adj.	Coefficient of multiple determination adjusted for sample size $R^2adj.=1-\left\{\left(\frac{n-1}{n-p}\right)\left(\frac{SSE}{SST}\right)\right\}$
Std. Dev.	Standard deviation
TOTDW	Total dry weight (i.e., stem plus leaf) kg/m^2
VI	Normalized vegetative index
VPD	Air vapor pressure deficit (Kpa)
YEAR	80 or 81 was used as an indicator variable in some statistical tests

1980 Canopy Temperature Regression Statistics

Statistical Model: $y = \beta_0 + \beta_1 X + \xi$

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P>F
Regression	1	150.805	150.810	54.41	0.0001
Error	35	97.008	2.770		
Corrected Total	36	274.813			

R^2= 0.6085 AVGTDIFF Mean= -4.17

R^2adj.= 0.5974 C.V.= -39.89

Parameter	Estimate	T for Ho: Parameter=0	Std. Error of Estimate	P>|T|
Intercept	1.078	1.41	0.7627	0.1665
VPD	-1.259	-7.38	0.0171	0.0001

Estimated Regression Function:

AVGTDIFF= 1.08 - 1.26VPD

Constraints on the equation:

W= (10.2, 12,7, or 15.2 cm irrigation water); Well-watered plants (see Idso et al., 1981) for model development.

1981 Canopy Temperature Regression Statistics

Statistical Model: $y = \beta_0 + \beta_1 X + \xi$

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P>F
Regression	1	178.421	178.421	344.11	0.0001
Error	58	30.073	0.5185		
Corrected Total	59	208.494			

R^2= 0.856 AVGTDIFF Mean= -3.22

R^2adj.= 0.855 C.V.= -22.36

Parameter	Estimate	T for Ho: Parameter=0	Std. Error of Estimate	P>!T!
Intercept	6.189	12.00	0.516	0.0001
VPD	-3.93	-18.56	0.021	0.0001

Estimated Regression Function:

AVGTDIFF= 6.19 - 3.93VPD

Constraints on the equation:

W= All treatments were used (see text); i.e., well-watered plants (see Idso et al., 1981) for model development.

1980 LAI Regression Statistics

Statistical Model: $y=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_2^2+\xi$

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P>F
Regression	3	120.8008	40.2699	275.06	0.0001
Error	61	8.9300	0.1464		
Corrected Total	64	129.7308			

R^2= 0.931 LAI Mean= 2.25 STD. DEV= 0.383

R^2adj.= 0.918 C.V.= 17.01

Parameter	Estimate	T for Ho: Parameter=0	Std. Error of Estimate	P>!T!
Intercept	-1.6062	-6.69	0.2401	0.0001
TOTDW	1.2587	25.85	0.0118	0.0001
GDD	0.0151	6.21	0.0024	0.0001
GDD	-3.359×10^{-5}	-6.18	5.43×10^{-6}	0.0001

Estimated Regression Function:

$$LAI= -1.61 + 1.26TOTDW + 0.015GDD - 3.36 \times 10^{-5}GDD2$$

Constraints on the equation:

$$0.027 \geq TOTDW \leq 0.450$$
$$0.2 \geq LAI \leq 5.7$$
$$87 \geq GDD \leq 438$$

1981 LAI Regression Statistics

Statistical Model: $y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_2^2 + \xi$

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P>F
Regression	3	58.7825	19.5942	150.19	0.0001
Error	61	8.9300	0.1305		
Corrected Total	64	66.7407			

R^2= 0.881 LAI Mean= 3.36 STD. DEV= 0.361

R^2adj.= 0.875 C.V.= 10.77

Parameter	Estimate	T for Ho: Parameter=0	Std. Error of Estimate	P>!T!
Intercept	-0.6847	-1.76	0.38883	0.0832
TOTDW	10.4432	17.32	0.01459	0.0001
GDD	0.0117	3.20	0.00365	0.0022
GDD2	-2.4359×10^{-5}	-3.27	7.46×10^{-6}	0.0018

Estimated Regression Function:

$$LAI = -0.685 + 10.44 TOTDW + 0.012 GDD - 2.44 \times 10^{-5} GDD2$$

Constraints on the equation:

$0.027 \geq TOTDW \leq 0.450$

$0.2 \geq LAI \leq 5.7$

$87 \geq GDD \leq 438$

Extra Sum Of Squares: An ANOVA method for testing equalitity of regression equations.

The specific test: To determine if the 1980 LAI regression equation is statistically equivalent to the 1981 LAI regression equation. If the equations are not significantly different, then a single equation may be used to describe the data.

Terminology

Full model: or unrestricted model, under the null hypothesis (Ho); assumes the two regression equations to be equal. Theoretically, the residual sum of squares of the two individual equations, when summed, is statistically equivalent to the error sum of squares of a regression equation developed from their composite data set.

Reduced model: or restricted model, under the alternative hypothesis (Ha); assumes the two regression equations are not equal. The regression equation formulated from a combinatorial data set occupies significantly different sample space than either data set does individually, invalidating the null hypothesis.

Symbols used

SSRES: Residual sum of squares (error; i.e., $\Sigma(y-\hat{y})^2$).

SSRES80: Residual sum of squares from 1980 LAI equation.

SSRES81: Residual sum of squares from 1981 LAI equation.

CMBQ: Residual sum of squares resulting from the combined data set.

Information for doing the test

	SSRES	D.F.	N
1980 Model	8.93	61	65
1981 Model	7.96	61	65
CMBQ Model	18.93	126	130

Hypothesis under consideration

Ho: $\beta_{0}80=\beta_{0}81$, $\beta_{1}80=\beta_{1}81$, $\beta_{2}80=\beta_{2}81$, and $\beta_{3}80=\beta_{3}81$
Ha: either one, two etc. parameters are not equal, or , all are not equal.

Calculations

$SSRES_{Full\ model}$ = SSE80 + SSE81
= 16.89

D.F.= (n-p)+(n+p)

=122

n=N1980
m=N1981
p=no. parameters estimated in the model.

$SSRES_{Reduced\ model}$= combined data set from both years, and "re-regressed."
=18.98

F-test statistic

$$F=\left[\left((SSRES_{\substack{Reduced\\model}} - SSRES_{\substack{Full\\model}}) / (x+1)(k-1)\right) \ / \ \left((SSRES_{\substack{Full\\model}}) / (D.F.)\right)\right]$$

=3.78

where;
x= no. independent variables
k= no. of models being compared

P>F (1- : 4,122)
> 0.0001

Would reject Ho and conclude, the reduced model is not as adequate as the full model.

Note: The results of the test statistic suggest the two equations differ by one or more parameters and remain unknown without further tests.

To find which parameters (i.e., slopes) are different, another test, the Likelihood-ratio, must be done. Very simply stated, the ratio test uses an independent discrete variable (called an indicator or dummy variable) in a equation containing all of the parameters being tested plus the indicator variable. All of the data from one year were assigned one value for the indicator variable and the other data were assigned another value. In this case, 80 was assigned to the 1980 data and 81 was assigned to the 1981 data.

The model is:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_2^2 + X_0$$

where; X_0 is the value of the indicator variable.

The method separates equations in coordinate space by the values associated with the indicator, combining aspects of regression and ANOVA so that many comparisons can be done simultaneously. The parameters are compared for non-parallel slopes; if the slopes are parallel, then they are equivalent. If the slopes are not equal; that is, if they have *elements* in the same set, these common points are detectable, both mathematically and graphically. The slope of the line tangent to a union in a set will be equal to zero (e.g., $\frac{dy}{dx}$ and $\frac{dx}{dy} = 0$; or, $f(x) - g(x) = 0$).

A summary of the results of the Likelihood-ratio test for estimating the differences between parameters of two regression equations is in this apendix. A variable like A*B (A 'cross' B) is a check for non-parallel slopes between A and B. Single variables check significant differences given that the other variables are in the model.

The Full Model: 1980 and 1981 (combined) LAI Regression

Statistics

Statistical model: $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_2^2 + x_0$

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P>F
Regression	3	217.172	73.307	480.51	0.0001
Error	126	18.983	9.151		
Corrected Total	129	236.155			

R^2= 0.920 LAI Mean= 2.8 STD. DEV= 0.388

R^2adj.= 0.918 C.V.= 13.85

Parameter	Estimate	T for Ho: Parameter=0	Std. Error of Estimate	P>!T!
Intercept	-1.3956	-6.73	0.02073	0.0001
TOTDW	12.076	33.28	0.00890	0.0001
GDD	0.0145	7.14	0.0020	0.0001
GDD2	-3.207×10^{-5}	-7.34	0.00001	0.0001

Estimated Regression Function:

LAI= $-1.40 + 12.1$TOTDW $+ 0.015$GDD $- 3.21 \times 10^{-5}$GDD2

Constraints on the equation:

0.027 $\geq$ TOTDW $\leq$ 0.450
87 $\geq$ GDD $\leq$ 438
0.2 $\geq$ GDD $\leq$ 5.7

Likelihood-Ratio Test Statistic: Testing the Dissimilarities between the 1980 and 1981 LAI Regression Equations

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P>F
Regression	7	219.27	31.32	226.28	0.0001
Error	122	16.89	0.138		
Corrected Total	129	234.16			

R^2= 0.928 LAI Mean= 2.80 STD. DEV= 0.372

R^2adj.= 0.924 C.V.= 13.28

Parameter	Degrees of Freedom	Type IV Sum of Squares	F-value	P>|F|
YEAR	1	0.0547	3.95	0.0491
TOTDW	1	120.3715	869.56	0.0001
TOTDW*YEAR	1	1.0432	7.54	0.0070
GDD	1	5.0358	36.38	0.0001
GDD*YEAR	1	0.0817	0.59	0.4440
GDD2	1	5.3457	38.62	0.0001
GDD2*YEAR	1	0.1355	0.98	0.3244

Indicator Variable:

Year as a factor, consisted of two levels:

Factor Level One: 80;

Factor Level Two: 81;

Constraints on the system:

$0.027 \geq$ TOTDW ≤ 0.450
$0.2 \geq$ LAI ≤ 5.7
$87 \geq$ GDD ≤ 438

Asymptotic Growth Model: Normalized Vegetative Index versus LAI for the 1980 Growning Season

Statistical model: $y=\beta_0\left(1-e^{-kx}\right)+\xi$

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
Regression	2	29.9093	14.9547
Error	63	0.6118	0.0097
Uncorrected Total	65	30.5211	
Corrected Total	64	1.2459	

R^2=0.509

R^2adj.=0.501

Parameter	Estimate	Asymptotic Error	Asymptotic 95% Confidence Interval Lower	Upper
β_0	0.7690	0.0194	0.7302	0.8079
LAI	1.4617	0.1451	1.1717	1.7517

Estimated Regression Function:

$$VI= 0.769 - 0.769e^{-(1.46LAI)}$$

Asymptotic Growth Model: Normalized Vegetative Index versus LAI for the 1981 Growning Season

Statistical model: $y = \beta_o\left(1 - e^{-kx}\right) + \xi$

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
Regression	2	21.6238	10.8119
Error	28	0.0281	0.0010
Uncorrected Total	30	21.6518	
Corrected Total	29	0.0555	

R^2=0.495

R^2adj.=0.477

Parameter	Estimate	Asymptotic Error	Asymptotic 95% Confidence Interval Lower	Upper
β_0	0.8736	0.0088	0.8557	0.8916
LAI	1.3402	0.1165	1.1015	1.5789

Estimated Regression Function:

$$VI = 0.874 - 0.874e^{-(1.34LAI)}$$

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APPENDIX B

GLOSSARY OF TERMS

USED IN APPENDIX B

AVGCT	Average canopy temperature (^{o}C)
AVGTDIFF	Average canopy minus air temperature (^{o}C)
LA	Leaf area (cm^2)
LAI	Leaf area index
LDW	Leaf dry weight (g/412.9 cm^2)
GDD	Growing degree day
N_VI	Normalized vegetative index
OBS	Observation number in the data set
REF_IR	Infrared reflectance (0.63μ- 0.69μ)
REF_RED	Red reflectance (0.76μ- 0.90μ)
SDW	Stem dry weight (g/412.9 cm^2)
TAIR	Ambient air temperature at the time readings were taken (^{o}C)
TOTDW	Total dry weight (g/412.9 cm^2)
VPD	Vapor pressure deficit (mb)
W	Irrigation treatment (inches of water)

NOTE: To convert dry weights from raw data collection form (i.e., g/412.9 cm^2) to standard metric form:

1) to g/m^2 , multiply by 24.21,

2) to kg/m^2 , multiply by 0.02421.

LEAF AREA AND RELATED DATA FOR 1980

OBS	DATE	LDW	SDW	TOTDW	LA	W	GDD	LAI
1	800617	3.30	3.27	6.57	543.80	5	86.94	1.31703
2	800617	4.64	4.24	8.88	733.77	0	86.94	1.77711
3	800617	2.20	1.43	3.63	329.64	0	86.94	0.79835
4	800617	2.40	3.20	5.60	454.65	4	86.94	1.10111
5	800617	3.10	2.40	5.50	576.86	2	86.94	1.39709
6	800617	2.73	3.50	6.23	469.10	3	86.94	1.13611
7	800617	2.40	3.40	5.80	421.36	5	86.94	1.02049
8	800617	1.93	3.00	4.93	285.17	2	86.94	0.69065
9	800617	1.90	2.00	4.10	325.67	3	86.94	0.78874
10	800617	3.63	4.16	7.79	596.33	6	86.94	1.44425
11	800617	3.30	2.95	6.25	626.74	1	86.94	1.51790
12	800617	4.60	3.60	8.20	941.50	4	86.94	2.28021
13	800617	1.66	1.44	3.10	309.90	1	86.94	0.75054
14	800617	3.70	4.17	7.87	612.02	6	86.94	1.48225
15	800617	3.40	1.96	5.36	554.63	3	86.94	1.34326
16	800617	2.90	2.73	5.63	430.34	6	86.94	1.04224
17	800617	3.55	3.20	6.75	621.59	5	86.94	1.50543
18	800624	4.99	3.81	8.80	1402.53	3	177.78	3.39678
19	800624	5.43	5.00	10.43	1328.65	2	177.78	3.21785
20	800624	4.70	4.06	8.76	1532.34	1	177.78	3.71116
21	800624	3.85	3.80	7.65	1046.75	5	177.78	2.53512
22	800624	8.09	8.35	16.44	2336.38	6	177.78	5.65846
23	800624	5.55	5.58	11.13	1652.77	4	177.78	4.00283
24	800624	3.68	2.52	6.20	502.73	0	177.78	1.21756
25	800627	6.58	6.25	12.83	1545.89	1	229.17	3.74398
26	800627	5.60	6.55	12.15	1259.60	0	229.17	3.05062
27	800627	6.66	7.36	14.02	1789.79	4	229.17	4.33468
28	800627	5.72	6.30	12.02	1270.57	2	229.17	3.07719
29	800627	4.54	4.20	8.74	1448.82	3	229.17	3.50889
30	800627	7.61	9.46	17.07	2256.82	5	229.17	5.46578
31	800627	3.85	3.42	7.27	693.16	0	229.17	1.67876
32	800627	1.47	1.09	2.56	454.58	2	229.17	1.10094
33	800627	1.86	2.35	4.21	631.61	4	229.17	1.52969
34	800701	6.15	6.49	12.64	1402.79	2	291.67	3.39741
35	800701	7.34	7.78	15.12	1926.30	3	291.67	4.66529
36	800701	5.22	5.54	10.76	1246.63	5	291.67	3.01921
37	800701	7.24	7.71	14.95	2064.09	1	291.67	4.99901
38	800701	6.33	6.77	13.10	1718.11	2	291.67	4.16108
39	800701	4.43	4.79	9.22	1137.98	0	291.67	2.75607
40	800701	8.90	9.68	18.58	2033.91	6	291.67	4.92591
41	800722	0.84	1.46	2.30	351.14	2	226.11	0.85042
42	800722	0.44	0.68	1.12	92.65	0	226.11	0.22439
43	800722	1.36	1.97	3.33	369.53	5	226.11	0.89496
44	800722	3.23	3.78	7.01	776.61	6	226.11	1.88067
45	800722	2.87	3.46	6.33	715.95	3	226.11	1.73395
46	800722	0.67	1.00	1.67	188.07	1	226.11	0.45549
47	800722	3.42	4.27	7.69	944.48	4	226.11	2.28743
48	800722	2.64	3.02	5.00	497.69	1	226.11	1.20535
49	800722	1.66	2.19	3.85	323.16	4	226.11	0.78266
50	800728	6.15	6.50	12.65	1691.90	6	308.89	4.09760
51	800728	2.85	2.70	5.55	749.01	1	308.89	1.81402
52	800728	4.80	4.95	9.75	1262.51	3	308.89	3.05767
53	800728	6.75	7.95	14.70	1930.86	5	308.89	4.67634
54	800728	2.50	1.70	4.20	398.00	1	308.89	0.96391
55	800728	3.10	3.00	6.10	858.28	2	308.89	2.07866
56	800728	1.00	0.55	1.55	191.18	0	308.89	0.46302
57	800728	5.70	5.90	11.60	1345.36	4	308.89	3.25832
58	800728	1.65	1.40	3.05	424.29	6	308.89	1.02759
59	800801	1.20	1.00	2.20	130.52	0	378.73	0.31611
60	800801	3.25	3.55	6.80	524.47	2	378.73	1.27021
61	800801	2.30	2.00	4.30	271.19	1	378.73	0.65679
62	800801	5.55	6.55	12.10	984.95	5	378.73	2.38544
63	800801	5.45	7.05	12.50	1308.46	2	378.73	3.16895
64	800801	6.00	6.40	12.40	1281.87	4	378.73	3.10455
65	800801	5.60	7.30	12.90	1245.72	3	378.73	3.01700

AVERAGE REFLECTANCE VALUES FOR 1980

OBS	DATE	W	TIME	REF_RED	REF_IR	N_VI
1	800617	0	1330	0.134629	0.401271	0.498723
2	800617	1	1330	0.106793	0.405367	0.583244
3	800617	2	1330	0.112414	0.395480	0.554568
4	800617	3	1330	0.111075	0.382768	0.548237
5	800617	4	1330	0.115893	0.360169	0.513742
6	800617	5	1330	0.105455	0.387006	0.568728
7	800617	6	1330	0.115893	0.365819	0.514854
8	800624	0	1430	0.070612	0.461594	0.726498
9	800624	1	1430	0.064900	0.551638	0.789397
10	800624	2	1430	0.063899	0.547246	0.790753
11	800624	3	1430	0.066078	0.557246	0.787886
12	800624	4	1430	0.065724	0.546812	0.785364
13	800624	5	1430	0.065636	0.544348	0.784658
14	800624	6	1430	0.064929	0.557826	0.791593
15	800627	0	1125	0.070896	0.495103	0.738046
16	800627	1	1125	0.065098	0.605870	0.805503
17	800627	2	1125	0.064958	0.603774	0.805054
18	800627	3	1125	0.066218	0.637466	0.811728
19	800627	4	1125	0.066863	0.631327	0.808439
20	800627	5	1125	0.065910	0.631626	0.810837
21	800627	6	1125	0.066723	0.619692	0.805352
22	800701	0	1425	0.138414	0.637044	0.630143
23	800701	1	1425	0.127941	0.775940	0.708438
24	800701	2	1425	0.126437	0.839660	0.732582
25	800701	3	1425	0.120260	0.885597	0.758859
26	800701	4	1425	0.120690	0.858098	0.751858
27	800701	5	1425	0.122408	0.918745	0.764367
28	800701	6	1425	0.119991	0.868357	0.756768
29	800722	0	1420	0.140449	0.413712	0.494186
30	800722	1	1420	0.109301	0.450650	0.601929
31	800722	2	1420	0.099032	0.462470	0.644976
32	800722	3	1420	0.099407	0.468196	0.650258
33	800722	4	1420	0.091948	0.446956	0.657789
34	800722	5	1420	0.095318	0.464502	0.659083
35	800722	6	1420	0.084395	0.427564	0.668100
36	800728	0	1500	0.118297	0.340841	0.487665
37	800728	1	1500	0.082153	0.406757	0.645375
38	800728	2	1500	0.062732	0.488889	0.771599
39	800728	3	1500	0.064755	0.516216	0.775899
40	800728	4	1500	0.063519	0.477327	0.761960
41	800728	5	1500	0.061355	0.505760	0.783488
42	800728	6	1500	0.061467	0.506607	0.782291
43	800801	0	1530	0.086306	0.355942	0.596607
44	800801	1	1530	0.067124	0.400435	0.696993
45	800801	2	1530	0.056834	0.468551	0.780850
46	800801	3	1530	0.054853	0.476812	0.790163
47	800801	4	1530	0.054522	0.471014	0.788892
48	800801	5	1530	0.053227	0.484928	0.799643
49	800801	6	1530	0.053481	0.505072	0.806834
50	800818	0	1330	0.109711	0.380275	0.546329
51	800818	1	1330	0.092913	0.409786	0.627683
52	800818	2	1330	0.097034	0.416055	0.620621

AVERAGE REFLECTANCE VALUES FOR 1980

OBS	DATE	W	TIME	REF_RED	REF_IR	N_VI
53	800818	3	1330	0.093517	0.410245	0.628071
54	800818	4	1330	0.091942	0.412844	0.635759
55	800818	5	1330	0.098924	0.424465	0.620638
56	800818	6	1330	0.089029	0.405810	0.640371
57	800820	0	1530	0.073481	0.380570	0.667342
58	800820	1	1530	0.061121	0.437688	0.753072
59	800820	2	1530	0.063481	0.446395	0.750328
60	800820	3	1530	0.061976	0.442881	0.754416
61	800820	4	1530	0.062183	0.435846	0.750317
62	800820	5	1530	0.063894	0.449246	0.750379
63	800820	6	1530	0.060973	0.427806	0.750278
64	800826	0	1151	0.083274	0.415858	0.654843
65	800826	1	1151	0.065130	0.515858	0.773426
66	800826	2	1151	0.064539	0.566181	0.795103
67	800826	3	1151	0.063505	0.584628	0.803797
68	800826	4	1151	0.063652	0.577558	0.801001
69	800826	5	1151	0.0636525	0.570227	0.798853
70	800826	6	1151	0.0646277	0.588188	0.801290
71	800902	0	1345	0.0804225	0.359350	0.634254
72	800902	1	1345	0.0560563	0.486179	0.793240
73	800902	2	1345	0.0602817	0.605691	0.818966
74	800902	3	1345	0.0518310	0.517886	0.818047
75	800902	4	1345	0.0519718	0.543902	0.825561
76	800902	6	1345	0.0567606	0.586179	0.823434

AVERAGE CANOPY TEMPERATURES FOR 1980

OBS	DATE	W	TIME	VPD	TAIR	AVGCT	AVGTDIFF
1	800617	0	1246	20.43	25.8	30.8833	5.0833
2	800617	1	1246	20.43	25.8	28.2333	2.4333
3	800617	2	1246	20.43	25.8	28.4500	2.6500
4	800617	3	1246	20.43	25.8	29.6833	3.8833
5	800617	4	1246	20.43	25.8	29.4333	3.6333
6	800617	5	1246	20.43	25.8	26.9500	1.1500
7	800617	6	1246	20.43	25.8	29.2333	3.4333
8	800624	0	1430	27.31	33.6	31.5500	-2.0500
9	800624	1	1430	27.31	33.6	30.4500	-3.1500
10	800624	2	1430	27.31	33.6	30.4333	-3.1667
11	800624	3	1430	27.31	33.6	30.4833	-3.1167
12	800624	4	1430	27.31	33.6	30.1500	-3.4500
13	800624	5	1430	27.31	33.6	30.3000	-3.3000
14	800624	6	1430	27.31	33.6	30.7333	-2.8667
15	800627	0	1335	68.83	41.1	37.8500	-3.2500
16	800627	1	1335	68.83	41.1	35.6167	-5.4833
17	800627	2	1335	68.83	41.1	34.9167	-6.1833
18	800627	3	1335	68.83	41.1	32.8500	-8.2500
19	800627	4	1335	68.83	41.1	33.1333	-7.9667
20	800627	5	1335	68.83	41.1	32.8833	-8.2167
21	800627	6	1335	68.83	41.1	32.5833	-8.5167
22	800701	0	1330	55.30	38.9	37.7333	-1.1667
23	800701	1	1330	55.30	38.9	36.2500	-2.6500
24	800701	2	1330	55.30	38.9	35.4500	-3.4500
25	800701	3	1330	55.30	38.9	33.2167	-5.6833
26	800701	4	1330	55.30	38.9	33.2000	-5.7000
27	800701	5	1330	55.30	38.9	32.7000	-6.2000
28	800701	6	1330	55.30	38.9	31.2667	-7.6333
29	800722	0	1420	32.95	29.7	34.8000	5.1000
30	800722	1	1420	32.95	29.7	31.5667	1.8667
31	800722	2	1420	32.95	29.7	29.6333	-0.0667
32	800722	3	1420	32.95	29.7	29.8333	0.1333
33	800722	4	1420	32.95	29.7	29.2667	-0.4333
34	800722	5	1420	32.95	29.7	29.9333	0.2333
35	800722	6	1420	32.95	29.7	29.4333	-0.2667
36	800728	0	1520	61.80	39.4	39.6667	0.2667
37	800728	1	1520	61.80	39.4	37.7000	-1.7000
38	800728	2	1520	61.80	39.4	34.0667	-5.3333
39	800728	3	1520	61.80	39.4	33.2167	-6.1833
40	800728	4	1520	61.80	39.4	33.2167	-6.1833
41	800728	5	1520	61.80	39.4	32.6500	-6.7500
42	800728	6	1520	61.80	39.4	32.1833	-7.2167
43	800801	0	1400	57.59	39.2	38.2500	-0.9500
44	800801	1	1400	57.59	39.2	37.8000	-1.4000
45	800801	2	1400	57.59	39.2	35.6333	-3.5667
46	800801	3	1400	57.59	39.2	34.3000	-4.9000
47	800801	4	1400	57.59	39.2	34.9333	-4.2667
48	800801	5	1400	57.59	39.2	34.1000	-5.1000
49	800801	6	1400	57.59	39.2	33.3333	-5.8667
50	800818	0	1200	33.07	33.9	32.6667	-1.2333
51	800818	1	1200	33.07	33.9	32.2667	-1.6333
52	800818	2	1200	33.07	33.9	31.8833	-2.0167
53	800818	3	1200	33.07	33.9	32.0500	-1.8500
54	800818	4	1200	33.07	33.9	31.9333	-1.9667
55	800818	5	1200	33.07	33.9	31.8500	-2.0500
56	800818	6	1200	33.07	33.9	31.9833	-1.9167
57	800819	0	1417	38.99	34.7	35.1000	0.4000
58	800819	1	1417	38.99	34.7	33.6000	-1.1000
59	800819	2	1240	38.99	34.7	32.2000	-2.5000
60	800819	3	1240	38.99	34.7	31.3000	-3.4000
61	800819	4	1240	38.99	34.7	31.7000	-3.0000
62	800819	6	1417	38.99	34.7	32.8000	-1.9000
63	800820	0	1345	23.99	30.8	31.6833	0.8833
64	800820	1	1345	23.99	30.8	30.8500	0.0500
65	800820	2	1345	23.99	30.8	31.3667	0.5667
66	800820	3	1345	23.99	30.8	30.6000	-0.2000
67	800820	4	1345	23.99	30.8	30.0333	-0.7667
68	800820	5	1345	23.99	30.8	30.8167	0.0167

AVERAGE CANOPY TEMPERATURES FOR 1980

OBS	DATE	W	TIME	VPD	TAIR	AVGCT	AVGTDIFF
69	800820	6	1345	23.99	30.8	29.9667	-0.833
70	800825	0	1320	48.78	36.7	36.1000	-0.600
71	800825	1	1320	48.78	36.7	36.1000	-0.600
72	800825	2	1230	48.78	36.7	32.0000	-4.700
73	800825	3	1230	48.78	36.7	31.4000	-5.300
74	800825	4	1230	48.78	36.7	30.3000	-6.400
75	800825	6	1320	48.78	36.7	30.6000	-6.100
76	800826	0	1100	41.07	34.4	31.0333	-3.367
77	800826	1	1100	41.07	34.4	30.1833	-4.217
78	800826	2	1100	41.07	34.4	28.5500	-5.850
79	800826	3	1100	41.07	34.4	27.8167	-6.583
80	800826	4	1100	41.07	34.4	27.5333	-6.867
81	800826	5	1100	41.07	34.4	27.3167	-7.083
82	800826	6	1100	41.07	34.4	27.3500	-7.050
83	800827	0	1200	9.78	24.4	23.7000	-0.700
84	800827	1	1200	9.78	24.4	23.1000	-1.300
85	800827	2	1130	9.78	24.4	23.0000	-1.400
86	800827	3	1130	9.78	24.4	22.4000	-2.000
87	800827	4	1130	9.78	24.4	22.5000	-1.900
88	800827	6	1200	9.78	24.4	22.3000	-2.100
89	800829	0	1500	46.18	35.6	37.9000	2.300
90	800829	1	1500	46.18	35.6	37.2000	1.600
91	800829	2	1500	46.18	35.6	35.2000	-0.400
92	800829	3	1500	46.18	35.6	33.0000	-2.600
93	800829	4	1500	46.18	35.6	32.1000	-3.500
94	800829	6	1500	46.18	35.6	32.0000	-3.600
95	800830	0	1530	38.62	34.4	25.3000	-9.100
96	800830	1	1530	38.62	34.4	25.5000	-8.900
97	800830	2	1530	38.62	34.4	25.3000	-9.100
98	800830	3	1500	38.62	34.4	24.3000	-10.100
99	800830	4	1500	38.62	34.4	24.2000	-10.200
100	800830	6	1500	38.62	34.4	23.3000	-11.100
101	800902	0	1300	24.85	31.1	28.7000	-2.400
102	800902	1	1300	24.85	31.1	28.6000	-2.500
103	800902	2	1300	24.85	31.1	28.3000	-2.800
104	800902	3	1230	24.85	31.1	27.2000	-3.900
105	800902	4	1230	24.85	31.1	27.2000	-3.900
106	800902	6	1230	24.85	31.1	27.3000	-3.800

LEAF AREA AND RELATED DATA FOR 1981

OBS	DATE	LA	W	LDW	SDW	TOTDW	GDC	LAI
1	810609	1831.15	0	6.34	6.27	12.61	170.83	4.43485
2	810609	1014.54	0	3.46	4.07	7.53	170.83	2.45711
3	810609	1824.97	0	7.27	6.78	14.05	170.83	4.41988
4	810609	1465.63	1	5.28	4.88	10.16	170.83	3.54960
5	810609	888.64	2	2.98	2.59	5.57	170.83	2.15219
6	810609	1549.08	2	5.67	5.84	11.51	170.83	3.75171
7	810609	1358.93	3	4.06	3.81	7.87	170.83	3.29118
8	810609	2218.30	3	7.30	8.74	16.04	170.83	5.37249
9	810609	1788.70	3	6.61	6.67	13.37	170.83	4.33204
10	810609	1392.59	4	4.98	4.69	9.67	170.83	3.37271
11	810609	898.03	4	3.19	2.82	6.01	170.83	2.17493
12	810609	1500.56	5	5.76	5.66	11.42	170.83	3.63420
13	810609	1247.86	6	4.81	4.10	8.91	170.83	3.02218
14	810609	1996.24	6	7.36	7.70	15.06	170.83	4.83468
15	810617	1278.05	0	4.56	5.56	10.12	271.67	3.09530
16	810617	1435.19	1	3.96	5.49	9.45	271.67	3.47588
17	810617	1546.63	2	4.76	6.03	10.79	271.67	3.74577
18	810617	1863.44	2	6.79	11.35	18.14	271.67	4.51305
19	810617	1756.11	3	5.50	7.66	13.16	271.67	4.25311
20	810617	1783.24	3	6.09	8.51	14.62	271.67	4.31882
21	810617	1672.40	4	5.98	9.15	15.13	271.67	4.05038
22	810617	1753.49	5	5.52	6.98	12.50	271.67	4.24677
23	810617	1128.91	6	3.27	5.09	8.36	271.67	2.73410
24	810618	1640.42	0	5.47	7.30	12.77	283.33	3.97292
25	810618	1358.09	0	4.98	6.63	11.61	283.33	3.28915
26	810618	1492.69	1	5.10	7.61	12.71	283.33	3.61514
27	810618	2271.70	1	8.03	10.16	18.19	283.33	5.50182
28	810618	2154.21	2	6.84	11.04	17.88	283.33	5.21727
29	810618	1319.05	3	4.69	5.65	10.34	283.33	3.19460
30	810618	1648.94	3	5.42	7.36	12.78	283.33	3.99356
31	810618	1682.15	4	6.46	10.14	16.60	283.33	4.07399
32	810618	1637.83	5	6.18	9.31	15.49	283.33	3.96665
33	810618	2071.60	6	7.15	9.99	17.14	283.33	5.01720
34	810713	918.61	0	3.74	3.45	7.19	118.61	2.22478
35	810713	1175.01	0	5.34	4.62	9.96	118.61	2.84575
36	810713	1009.99	1	4.73	3.91	8.64	118.61	2.44609
37	810713	1076.50	1	5.23	5.03	10.26	118.61	2.60717
38	810713	1140.38	2	4.48	4.00	8.48	118.61	2.76188
39	810713	757.34	3	3.39	3.10	6.49	118.61	1.83420
40	810713	946.94	4	3.82	3.58	7.40	118.61	2.29339
41	810713	685.90	5	3.13	2.36	5.49	118.61	1.66118
42	810713	1349.14	5	5.92	5.52	11.44	118.61	3.26747
43	810713	552.07	6	2.57	2.26	4.83	118.61	1.33705
44	810713	1209.02	6	6.07	6.26	12.33	118.61	2.92812
45	810716	972.62	0	4.52	5.46	9.98	170.56	2.35558
46	810716	706.02	1	3.20	2.73	5.93	170.56	1.70991
47	810716	885.19	2	3.22	3.54	6.76	170.56	2.14384
48	810716	981.92	3	4.06	4.02	8.08	170.56	2.37811
49	810716	1042.95	4	4.43	4.56	8.99	170.56	2.52591
50	810716	1631.33	5	5.91	5.96	11.87	170.56	3.95091
51	810716	647.48	5	2.67	2.05	4.72	170.56	1.56813
52	810716	1376.43	5	6.05	5.60	11.65	170.56	3.33357
53	810716	535.06	6	2.65	2.23	4.88	170.56	1.29586
54	810716	1553.89	6	6.27	6.19	12.46	170.56	3.76336
55	810723	1371.23	0	4.26	4.94	9.20	278.61	3.32097
56	810723	1720.20	2	5.77	7.18	12.95	278.61	4.16614
57	810723	994.13	3	2.86	3.74	6.60	278.61	2.40768
58	810723	1563.10	4	4.74	7.23	11.97	278.61	3.78566
59	810723	1394.45	5	4.45	5.74	10.19	278.61	3.37721
60	810723	1874.49	6	6.79	10.14	16.93	278.61	4.53982
61	810731	1463.55	0	5.75	8.67	14.42	383.33	3.54456
62	810731	2128.15	1	6.37	10.90	17.27	383.33	5.15415
63	810731	1102.05	3	3.46	5.37	8.83	383.33	2.66905
64	810731	1486.96	4	5.04	10.02	15.06	383.33	3.60126
65	810731	1308.67	5	3.92	6.29	10.21	383.33	3.16946

AVERAGE REFLECTANCE VALUES FOR 1981

CBS	DATE	W	TIME	REF_RED	REF_IR	N_VI
1	810609	0	1430	0.0422880	0.599111	0.868011
2	810609	1	1430	0.0394737	0.580667	0.871983
3	810609	2	1430	0.0405702	0.603778	0.873718
4	810609	3	1430	0.0410453	0.599778	0.871479
5	810609	4	1430	0.0413743	0.610222	0.873015
6	810609	5	1430	0.0421784	0.614889	0.871620
7	810609	6	1430	0.0414108	0.592222	0.869100
8	810617	0	1200	0.0384115	0.686693	0.894049
9	810617	1	1200	0.0374023	0.710948	0.900019
10	810617	2	1200	0.0385742	0.732977	0.900068
11	810617	3	1200	0.0382161	0.736538	0.901317
12	810617	4	1200	0.0369141	0.720961	0.902585
13	810617	5	1200	0.0385417	0.728527	0.899462
14	810617	6	1200	0.0390625	0.742323	0.900037
15	810625	0	1100	0.0330447	0.645145	0.902564
16	810625	1	1100	0.0325758	0.666917	0.906735
17	810625	2	1100	0.0327922	0.673173	0.907037
18	810625	3	1100	0.0334416	0.711461	0.910212
19	810625	4	1100	0.0333694	0.711962	0.910352
20	810625	5	1100	0.0318903	0.680180	0.910412
21	810625	6	1100	0.0333694	0.726727	0.912139
22	810713	0	1100	0.0477333	0.458883	0.811614
23	810713	1	1100	0.0430333	0.438654	0.819668
24	810713	2	1100	0.0442030	0.443931	0.817693
25	810713	3	1100	0.0477333	0.413149	0.791951
26	810713	4	1100	0.0444000	0.424142	0.809958
27	810713	5	1100	0.0445000	0.416887	0.806617
28	810713	6	1100	0.0447333	0.389622	0.792241
29	810818	0	1020	0.0480114	0.476661	0.816997
30	810818	1	1020	0.0456676	0.515709	0.837229
31	810818	2	1020	0.0474432	0.483662	0.820863
32	810818	3	1020	0.0465199	0.470826	0.819839
33	810818	4	1020	0.0491477	0.476661	0.812996
34	810818	5	1020	0.0478409	0.458887	0.809285
35	810818	6	1020	0.0465909	0.415619	0.796884
36	810825	0	1525	0.0374157	0.513848	0.864163
37	810825	1	1525	0.0376404	0.500972	0.859666
38	810825	2	1525	0.0389139	0.517736	0.860252
39	810825	3	1525	0.0376404	0.499514	0.859645
40	810825	4	1525	0.0393633	0.474490	0.846429
41	810825	5	1525	0.0380150	0.496113	0.857438
42	810825	6	1525	0.0376404	0.463800	0.848525
43	810829	0	1245	0.0406188	0.524042	0.856053
44	810829	1	1245	0.0365602	0.529340	0.870323
45	810829	2	1245	0.0357285	0.525265	0.872521
46	810829	3	1245	0.0354291	0.530766	0.874918
47	810829	4	1245	0.0430140	0.508150	0.843430
48	810829	5	1245	0.0345642	0.524450	0.875940
49	810829	6	1245	0.0375250	0.496536	0.858884
50	810912	0	1359	0.0281739	0.559019	0.903983
51	810912	1	1359	0.0287992	0.573150	0.904295
52	810912	2	1359	0.0281739	0.562760	0.904606
53	810912	3	1359	0.0290807	0.571488	0.903150
54	810912	4	1359	0.0292683	0.575852	0.903203
55	810912	5	1359	0.0289869	0.587074	0.905820
56	810912	6	1359	0.0289556	0.582294	0.905254

AVERAGE CANOPY TEMPERATURES FOR 1981

OBS	DATE	W	TIME	VPD	TAIR	AVGCT	AVGTDIFF
1	810609	0	1500	23.26	35.6	32.4833	-3.1167
2	810609	1	1500	23.26	35.6	32.2000	-3.4000
3	810609	2	1500	23.26	35.6	31.8500	-3.7500
4	810609	3	1500	23.26	35.6	32.2333	-3.3667
5	810609	4	1500	23.26	35.6	31.7000	-3.9000
6	810609	5	1500	23.26	35.6	32.3000	-3.3000
7	810609	6	1500	23.26	35.6	32.2333	-3.3667
8	810617	0	1100	27.98	26.1	21.8833	-4.2167
9	810617	1	1100	27.98	26.1	21.9667	-4.1333
10	810617	2	1100	27.98	26.1	21.9167	-4.1833
11	810617	3	1100	27.98	26.1	21.5167	-4.5833
12	810617	4	1100	27.98	26.1	21.8167	-4.2833
13	810617	5	1100	27.98	26.1	21.6000	-4.5000
14	810617	6	1100	27.98	26.1	21.6333	-4.4667
15	810624	0	1530	30.70	34.7	28.9167	-5.7833
16	810624	1	1530	30.70	34.7	29.0667	-5.6333
17	810624	2	1530	30.70	34.7	28.5667	-6.1333
18	810624	3	1530	30.70	34.7	28.3167	-6.3833
19	810624	4	1530	30.70	34.7	28.2333	-6.4667
20	810624	5	1530	30.70	34.7	28.4667	-6.2333
21	810624	6	1530	30.70	34.7	28.3000	-6.4000
22	810713	0	1010	25.30	33.1	28.7833	-4.3167
23	810713	1	1010	25.30	33.1	28.8000	-4.3000
24	810713	2	1010	25.30	33.1	28.8500	-4.2500
25	810713	3	1010	25.30	33.1	28.8667	-4.2333
26	810713	4	1010	25.30	33.1	29.1000	-4.0000
27	810713	5	1010	25.30	33.1	28.7667	-4.3333
28	810713	6	1010	25.30	33.1	29.0000	-4.1000
29	810818	0	1540	18.10	23.9	23.4667	-0.4333
30	810818	1	1540	18.10	23.9	23.8167	-0.0833
31	810818	2	1540	18.10	23.9	24.0333	0.1333
32	810818	3	1540	18.10	23.9	24.3333	0.4333
33	810818	4	1540	18.10	23.9	23.2000	-0.7000
34	810818	5	1540	18.10	23.9	24.0833	0.1833
35	810818	6	1540	18.10	23.9	23.8833	-0.0167
36	810821	0	1530	26.42	28.1	24.6333	-3.4667
37	810821	1	1530	26.42	28.1	24.9667	-3.1333
38	810821	2	1530	26.42	28.1	24.4500	-3.6500
39	810821	3	1530	26.42	28.1	24.7333	-3.3667
40	810821	4	1530	26.42	28.1	24.6667	-3.4333
41	810821	5	1530	26.42	28.1	24.7667	-3.3333
42	810821	6	1530	26.42	28.1	24.7000	-3.4000
43	810827	0	1500	13.94	23.9	24.1000	0.2000
44	810827	2	1500	13.94	23.9	24.1000	0.2000
45	810827	4	1500	13.94	23.9	23.6000	-0.3000
46	810827	6	1500	13.94	23.9	24.3500	0.4500
47	810829	0	1130	23.16	29.4	25.5500	-3.8500
48	810829	1	1130	23.16	29.4	25.4000	-4.0000
49	810829	2	1130	23.16	29.4	25.3000	-4.1000
50	810829	3	1130	23.16	29.4	25.0667	-4.3333
51	810829	4	1130	23.16	29.4	25.4500	-3.9500
52	810829	5	1130	23.16	29.4	25.5000	-3.9000
53	810829	6	1130	23.16	29.4	25.3833	-4.0167
54	810908	0	1141	22.31	24.4	22.6500	-1.7500
55	810908	1	1141	22.31	24.4	22.5000	-1.9000
56	810908	2	1141	22.31	24.4	22.2333	-2.1667
57	810908	3	1141	22.31	24.4	22.5333	-1.8667
58	810908	4	1141	22.31	24.4	22.0333	-2.3667
59	810908	5	1141	22.31	24.4	22.2000	-2.2000
60	810908	6	1141	22.31	24.4	22.4500	-1.9500

GROWTH, CANOPY TEMPERATURE, AND SPECTRAL REFLECTANCE OF ALFALFA UNDER DIFFERENT IRRIGATION TREATMENTS

by

DAVID ERNEST JOHNSON, JR.

B.S., UNIVERSITY OF ARIZONA, 1978

AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

MASTER OF SCIENCE

Department of Agronomy

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1982

Growth, Canopy Temprature, and Spectral Reflectance

of Alfalfa Under Different Irrigation Treatments

by

David Ernest Johnson, Jr.

(Under the supervision of Drs. E.T. Kanemasu and M.B. Kirkham)

ABSTRACT

Alfalfa (Medicago sativa L. 'Cody') was grown under seven watering regimes to determine the effect of water on growth, canopy temperature, and spectral reflectance of alfalfa in the Southern Great Plains. Irrigation water (0, 2.5, 5.1, 7.6, 10.2, 12.7, or 15.2 cm) was added after each of three harvests in both 1980 and 1981. Throughout the growth period in both years, leaf area, stem dry weight (SDW), leaf dry weight (LDW), soil moisture, canopy temperature, and crop reflectance were measured. Soil moisture, leaf area, canopy temperature, and reflectance were analyzed using, respectively, a neutron-attenuation probe, an optical scanning meter, an infrared thermometer, and a hand-held radiometer. Vegetative yield was determined at harvests in July, August, September, and November of 1980, and May, June, July, August, and September of 1981. Variation in weather between the two summers enabled a comparison of data

from a stressed year in 1980 with those from a wet year in 1981.

In 1980, non-irrigated plants usually had the lowest yield, and plants irrigated with 5.1, 7.6, 10.2, 12.7, and 15.2 cm water generally had significantaly higher yield. In 1981, yield of non-irrigated plants was similar to that of irrigated plants. The ratio of LDW to total dry weight was about one-half, and this ratio remained relatively constant between irrigation treatments and years.

In both 1980 and 1981, the relationship between canopy-minus-air temperature ($T_c - T_a$) versus vapor-pressure deficit (VPD) was determined for well-watered alfalfa. In the dry year of 1980, irrigated plots had cooler canopy temperatures than did dryland plots, but differences in temperature due to level of water added were not apparent. In the wet year of 1981, differences in canopy temperature due to treatment were not evident. In both the dry year and the wet year, $T_c - T_a$ was inversely related to VPD.

A normalized vegetative index (VI), obtained by calculating a ratio of the difference of thematic mapper bands TM4 (0.76 to 0.90 µm) and TM3 (0.63 to 0.69 µm) [(TM4 - TM3)/(TM4 + TM3)] was directly related to leaf-area index. In 1980, dryland plants had the lowest VI, but differences due to amount of irrigation water added were not evident. In 1981, there was no significant difference between VI of irrigated plants and dryland plants.