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Nitrogen Fertility Influence on Water Stress and Yield of Winter Wheat

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ABSTRACT

Available soil water and N fertility are the primary factors limiting dryland winter wheat (*Triticum aestivum* L.) yields in the Central Great Plains. The objective of this field study was to determine how the level of N fertilization influences water use, water stress, and yield of dryland winter wheat grown in this area. The study was conducted during the 1988 and 1990 growing seasons on a Platner loam (fine, montmorillonitic, mesic Aridic Paleustoll) near Akron, CO. Nitrogen fertilizer was broadcast as NH_4NO_3 at 0, 28, 56, 84, and 112 kg N ha^{-1}. Canopy temperatures were measured with an infrared thermometer and used to compute the crop water stress index (CWSI). Evapotranspiration was computed and rooting depth inferred from weekly neutron probe readings of soil water content. In general, plant height, above-ground biomass, leaf area index, rooting depth, water use, and grain yield increased with increasing N. Values of CWSI declined after rain and increased as soil water again became limiting. Nitrogen treatment effects on CWSI varied with the severity of water stress. When CWSI <0.38, increasing N rate decreased water stress because a slight increase in rooting volume resulted. When CWSI >0.38, increasing N rate increased water stress because the excessive transpirational demand of the resulting larger leaf area and vegetative mass was not fully compensated by the increased rooting volume. Grain yield averaged over the 2 yr increased with increasing N up through the 56 kg ha^{-1} rate. The effect of N fertility on water use efficiency (WUE) was significantly different between years, with WUE increasing with increasing N up through the 56 and 84 kg ha^{-1} rates in 1988 and 1990, respectively. Grain yield was linearly correlated with cumulative evapotranspiration. Increasing levels of N fertility can be detrimental to winter wheat yields when water-limiting conditions reduce evapotranspiration rates to less than 62% of potential evapotranspiration.

AVAILABLE SOIL WATER and N fertility are the primary factors limiting winter wheat yields in the Central Great Plains. These two factors are related in that increased N fertility can stimulate deeper rooting by winter wheat (Brown, 1971), making a greater quantity of stored soil water available to the plant, thereby reducing potential water stress. However, larger above-ground biomass stimulated by increased N availability results in greater transpiration demands (Ritchie and Johnson, 1990). Thus, if sufficient soil water reserves are not available, greater water stress in high N treatments would also occur, possibly during later critical crop development stages, thereby reducing yield and water use efficiency (Howell, 1990). Heading, flowering, and grainfilling are the most critical growth stages in winter wheat with respect to water requirement (Musick, 1963; Singh, 1981; Kirkham and Kanemasu, 1983).

Musick and Dusek (1980) found that water stress during vegetative growth stages limits leaf and tiller development of winter wheat, while water stress during jointing increases rate of senescence and decreases

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Abbreviations: CWSI, crop water stress index; DOY, day of the year; CET, cumulative evapotranspiration; IRT, infrared thermometer; LAI, leaf area index; and WUE, water use efficiency.

number of spikelets per head. Fertilizer applications generally do not affect crop water use unless there are significant effects on leaf area development (Howell, 1990). Hatfield et al. (1988) found that evapotranspiration by winter wheat was not affected by N level, but that grain yield, above-ground biomass, and water use efficiency were increased with increasing N. Onken et al. (1990) found that water use efficiency based on final grain yield and cumulative growing season evapotranspiration increased significantly with increased N fertility for winter wheat grown in the Central Great Plains. Rhoads (1984) reported that when N was limiting yield, water use efficiency was improved by as much as 41% under high N application rates.

Blad et al. (1988) used canopy temperatures measured with infrared thermometers to evaluate the influence of N on water stress in winter wheat at five locations across the North American Great Plains. They found the effect of N fertilization on canopy temperature and water stress was not consistent among locations during the years of the study. They encouraged further research to explain the influence of N fertility on wheat canopy temperatures.

The objective of this study was to determine how N fertilization rate influences water use, water stress, growth, and yield of winter wheat grown under dryland conditions in the Central Great Plains.

MATERIALS AND METHODS

'TAM 107' winter wheat was planted in a Platner loam on 14 Sept. 1987 and 18 Sept. 1989 at a rate of 68 kg ha^{-1} at the Central Great Plains Research Station (40° 9′ N, 103° 9′ W, 1384 m above mean sea level), 6.4 km east of Akron, CO. Row direction was north-south. The experimental design was a randomized complete block (four replicates) with five N fertilizer treatments (0, 28, 56, 84, 112 kg N ha^{-1} broadcast as NH_4NO_3 just prior to planting). Individual plots were 9.1 by 12.2 m. Corn (*Zea mays* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] were grown on adjacent halves of each plot, followed by an 11-mo no-till chemical fallow period just prior to no-till wheat planting. Weeds were controlled during the fallow period with contact herbicides. No additional herbicide applications were necessary during the wheat growing season. All yield and above-ground biomass data were averaged for the two halves of each plot.

Soil water was measured at the center of each plot weekly from early April until grain harvest with a neutron probe (Model 3321, Troxler Electronic Lab., Research Triangle Park, NC)[1] at depths of 0.15, 0.46, 0.76, 1.06, 1.37, and 1.68 m. The data were used to calculate evapotranspiration by the water balance method (Rosenberg et al., 1983). Available water in the profile was calculated assuming a volumetric water content at the wilting point of 0.106 m^3 m^{-3}. Runoff and deep percolation were assumed to be negligible under these rainfed, no-till conditions. Rooting depth was inferred from changes in soil water content by depth (Bauer et al., 1989). A change in water content of at least 2 mm per 0.3 m soil layer between successive measurement dates was assumed to have been due to root extraction. The neutron probe was calibrated at the beginning of each season against gravimetric soil water data collected at the time of access tube installation. Crop height was measured and growth stage was determined weekly, defined using the Feekes scale (Large, 1954). Total above-ground biomass was measured at heading and maturity. In 1990, periodic measurements of leaf area index (LAI) were made with a plant canopy analyzer (LAI-2000, Li-Cor, Inc., Lincoln, NE) which employs a radiative transfer model to estimate LAI from readings of light interception by the crop canopy. Grain yield was harvested with a plot combine in early July from two 29.7-m^2 areas in the center of each plot. Grain yields were adjusted to 120 g kg^{-1}.

Canopy temperatures were measured with a hand-held infrared thermometer (IRT) with a 3° field of view, detecting radiation in the 8- to 14-micron waveband (Model 112 Agritherm, Everest Interscience, Fullerton, CA). Spot size ranged from 0.61 to 0.97 m^2, depending on IRT height and canopy height. Measurements were made two to three times a week between 1300 and 1400 h MDT when the sun was unobscured by clouds. Data were recorded with a portable data logger (Polycorder, Model 516B, Omnidata International, Logan, UT). The IRT was calibrated before and after each daily measurement period using a blackbody reference. The IRT was hand-held at approximately 1.5 m above the soil surface. Six instantaneous measurements were made from both the SE and SW corners of each plot to insure that no soil surface was viewed. Air temperature and vapor pressure deficit were measured at a height of 1.5 m before and after each measurement period with an Assman-type psychrometer (Model 5230, WeatherMeasure, Sacramento, CA) in an open area adjacent to the plots. The twelve canopy temperature measurements per plot were averaged and used with the average air temperature and vapor pressure deficit to calculate one Crop Water Stress Index (CWSI) value per plot. The CWSI was calculated following the method given by Idso et al. (1981) using the pre-heading and post-heading baseline equations for winter wheat given by Idso (1982).

In 1988, soil temperature was measured at 51 mm below the soil surface in one replication of the 0, 56, and the 112 kg N ha^{-1} treatments with five copper-constantan thermocouples wired in parallel. The data were logged with a battery-powered data logger (CR21X, Campbell Scientific, Logan, UT) at 1-min intervals and averaged throughout the 30-min period during which canopy temperatures were being measured. In 1990, a similar system was used to record soil temperatures and air temperatures at crop canopy height in one replication of all five N treatments.

RESULTS AND DISCUSSION

Precipitation during the approximately 4-mo growing season was variable throughout the 2 yr of the experiment (Table 1). Seasonal totals show 1988 above average and 1990 average. Distribution of precipitation throughout the growing season varied each year. Combined March and April precipitation was below average in 1988 and above average in 1990. May precipitation was 183% of average in 1988 and 131% of average in 1990. June precipitation was below average in both years.

These differences in precipitation patterns caused the timing and severity of water stress to be different between years (Fig. 1, 2). In 1988, large reductions in CWSI occurred in response to heavy rain prior to jointing and heading (Fig. 1). Light rain during heading and flowering maintained CWSI at less than 0.3. Crop water stress index increased from 0.3 to 0.7 through late grain filling due to low precipitation. During 1990, the heaviest precipitation period was between day of the year (DOY) 145 and 152, resulting in low water stress following heading and during flowering. Two

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[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA.

Table 1. Growing season precipitation for 1988, 1990, and 83-year average at Akron, CO.

Month	1988	1990	83-yr average
	mm		
March	32	43	21
April	16	37	43
May	141	101	77
June	42	23	63
Total	231	204	204

storms between DOY 159 and 165 moderated water stress briefly, but the following period with no precipitation caused CWSI to increase to severe levels through grain-filling. Statistically significant differences ($P \leq 0.10$) between CWSI values due to N treatment occurred for 85 and 61% of the measurement times in 1988 and 1990, respectively (Table 2).

The interaction between N fertility and water stress can be seen in Fig. 3, where CWSI values from each N treatment on a given day were plotted against the average CWSI value across all N treatments for that day. Linear regressions were fitted to the data and are shown in Fig. 3 without the data points. The data from both years were combined into one figure after noting that the slopes of the regression lines relative to each other were the same in both years. The slopes of all regression lines in Fig. 3 were statistically different from each other except for the 84 and 112 kg ha^{-1} lines. The lines cross at an average point of CWSI = 0.38. When water stress was mild (CWSI <0.38), increasing levels of N fertility decreased water stress. When water stress was moderate and severe (CWSI >0.38), increasing levels of N fertility increased water stress.

Table 2. Probability (*P*) of rejecting the null hypothesis of no difference in crop water stress index (CWSI) due to N treatment, and least significant difference at α = 0.05 (LSD 0.05) for separation of CWSI values.

1988			1990		
DOY†	*P*	LSD (0.05)	DOY	*P*	LSD (0.05)
120	0.00	0.11	127	0.12	0.10
125	0.17	0.11	134	0.44	0.11
126	0.06	0.07	138	0.01	0.07
132	0.00	0.06	141	0.02	0.14
134	0.00	0.04	143	0.01	0.07
137	0.00	0.05	145	0.05	0.10
138	0.08	0.09	151	0.39	0.11
146	0.00	0.05	154	0.01	0.11
147	0.00	0.04	155	0.00	0.02
155	0.00	0.10	156	0.03	0.11
156	0.00	0.08	157	0.88	0.10
158	0.09	0.10	158	0.64	0.13
159	0.01	0.08	159	0.17	0.09
160	0.02	0.09	160	0.24	0.08
162	0.01	0.06	162	0.00	0.04
166	0.21	0.12	163	0.18	0.14
167	0.44	0.09	164	0.05	0.15
168	0.00	0.06	165	0.00	0.11
169	0.01	0.07	168	0.00	0.12
172	0.05	0.06	169	0.00	0.06
			170	0.04	0.12
			171	0.02	0.20
			172	0.76	0.28
			173	0.65	0.14
			174	0.01	0.06
			176	0.01	0.08
			177	0.00	0.07
			178	0.25	0.06

† DOY = day of year.

Higher rates of N fertilization resulted in significantly larger plants with greater LAI and above-ground biomass (Table 3), which increased the evaporative

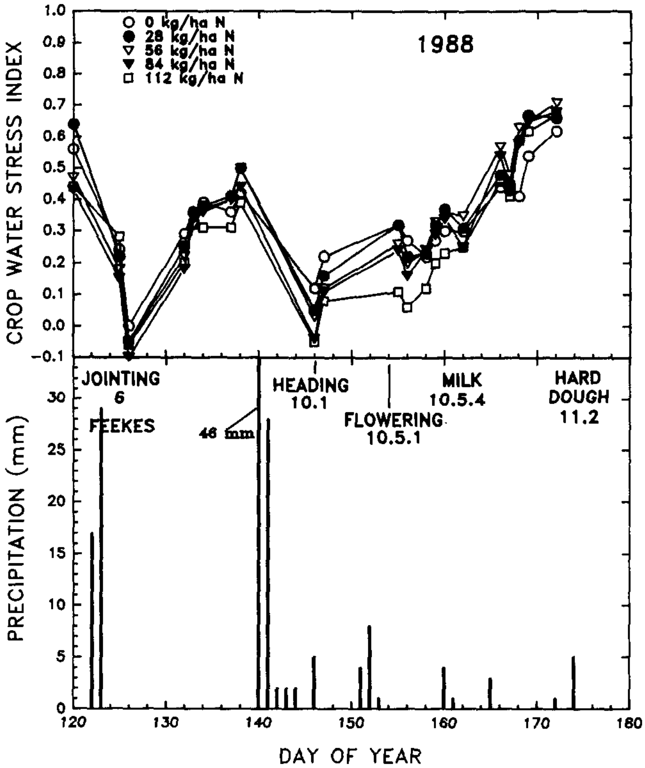

Fig. 1. Crop Water Stress Index of winter wheat in 1988 as influenced by N fertilizer treatments, and growing season precipitation.

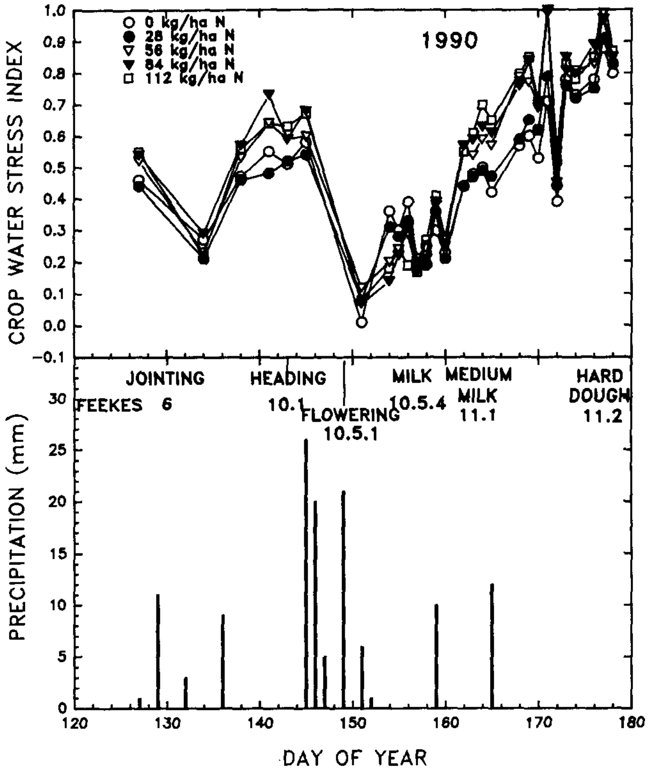

Fig. 2. Crop Water Stress Index of winter wheat in 1990 as influenced by N fertilizer treatments, and growing season precipitation.

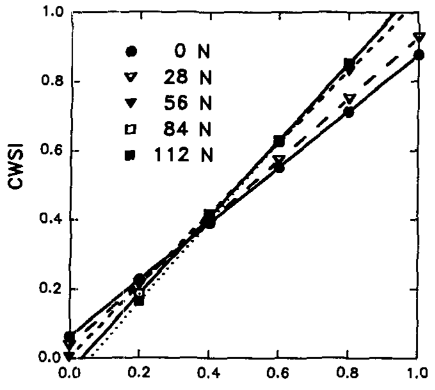

Fig. 3. Interaction of N fertility and level of water stress quantified with the Crop Water Stress Index (CWSI).

demand for water. Rooting depth was increased by N fertilization in 1988. In 1990, a non-significant trend for increased rooting depth with increasing N fertilization was also noted. Similar results regarding increased water extraction from deeper in the soil profile by wheat under increased N fertilization have been reported by Brown (1971) and Read et al. (1982). The increased rooting depth due to increased N may have provided slightly more available soil water for the plants, but this small increase in available water was only effective in moderating mild water stress (CWSI <0.38). Under conditions when water stress was more severe (CWSI >0.38), the larger transpirational demand resulting from the larger plants in the high-N treatments was not compensated adequately by the slightly greater rooting volume, and the result was increased water stress.

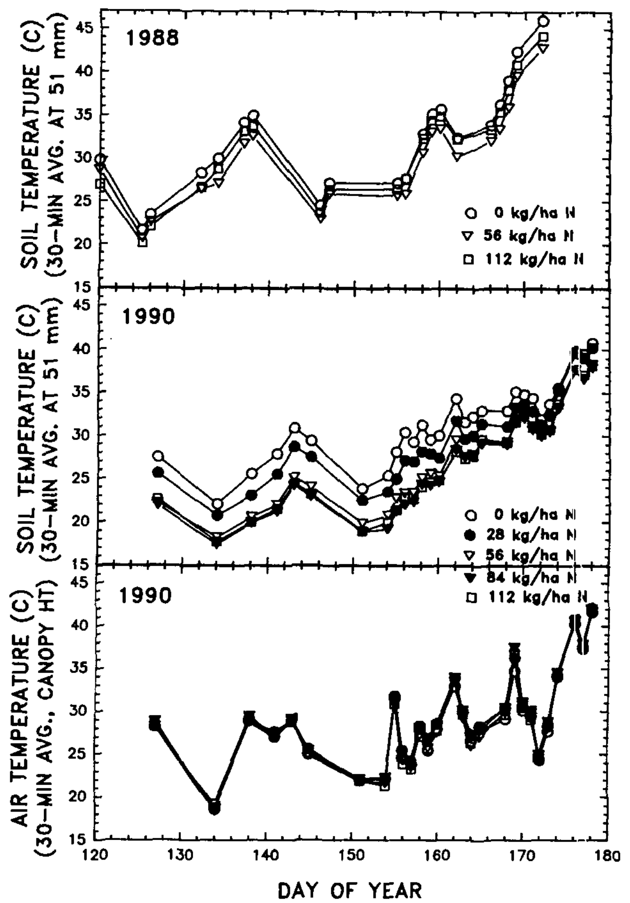

Fig. 4. The 30-min average soil temperature at 51 mm under a winter wheat canopy (1988 and 1990), and 30-min average air temperature at canopy height (1990) as influenced by N fertilizer treatments. Data are reported only for time during which infrared thermometer readings were made.

The increased above-ground biomass and LAI with increasing N in 1988 and 1990 substantially decreased the amount of solar irradiance reaching the soil surface, as noted by visual observations. Morgan (1988) similarly noted increased leaf area and above-ground biomass development in spring wheat with a 100 kg ha^{-1} N application which resulted in approximately 30% greater interception of incoming photosynthetically active radiation. In the present study this increased interception of solar irradiance decreased soil temperatures (Fig. 4). This increased thermal energy

Table 3. Effect of nitrogen fertility on maximum winter wheat height, leaf area index (LAI), rooting depth (estimated by depth of water extraction), total above-ground biomass at heading and harvest, heads ha^{-1}, grain yield, test weight, cumulative evapotranspiration (CET), and water use efficiency of winter wheat.

Nitrogen treatment	Maximum plant height	LAI	Rooting depth	Above-ground biomass at		Heads	Grain yield†	Test weight	CET	Water use efficiency
				Heading	Harvest					
kg ha^{-1}	m		m	kg ha^{-1}	kg ha^{-1}	million ha^{-1}	kg ha^{-1}	kg m^{-3}	mm	kg ha^{-1} mm^{-1}
1988										
0	0.51	not taken	1.1	6403	5376	5.21	1824	725	285	6.41
28	0.52		1.2	8072	6988	5.83	2134	704	299	7.09
56	0.54		1.5	9449	8084	7.06	2692	687	328	8.14
84	0.56		1.5	10307	9560	7.81	2833	673	327	8.64
112	0.55		1.5	9046	8303	7.01	2397	676	329	7.18
LSD (0.05)	NS		0.4	2149	2152	0.60	873	16	44	2.06
1990										
0	0.66	1.16	1.2	4481	3983	3.32	1433	776	224	6.43
28	0.78	1.95	1.4	6881	6225	5.27	2603	774	282	9.23
56	0.76	3.04	1.3	8916	7750	6.46	3086	765	276	11.25
84	0.80	3.20	1.5	7687	7113	5.46	2804	757	286	9.79
112	0.82	3.49	1.5	9713	6710	7.76	2914	753	288	10.13
LSD (0.05)	0.08	0.29	NS	2234	1129	1.51	279	4	29	0.94

† Grain yield at 120 g kg^{-1} moisture.

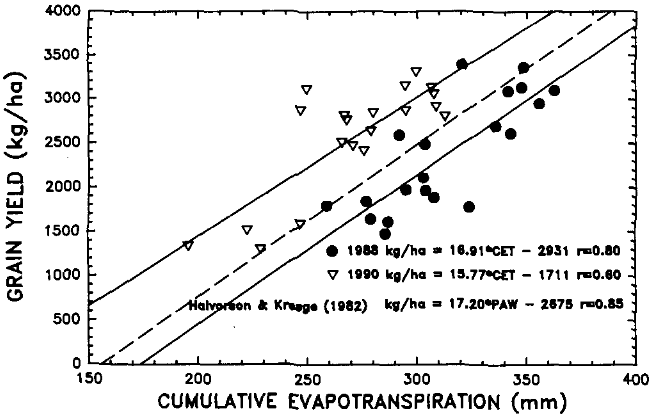

Fig. 5. Relationship between cumulative growing season evapotranspiration (CET) and winter wheat grain yield. (PAW = Plant Available Water, mm.)

in the low N treatments was transferred convectively and radiatively to the overlying canopy, although we were not able to detect it with measurements of air temperature at the top of the canopy during times when canopy temperatures were being measured with the IRT (Fig. 4). Perhaps the increased heat load from the warmer soil surfaces in the low-N plots was offset by increased mixing of air at the top of these canopies due to bouyancy effects and increased roughness from the more open canopies (Hatfield et al., 1985). Using non-water-stressed baselines for partial canopies as suggested by Hatfield et al. (1985) instead of the non-water-stressed baseline for full canopies used in this study, might have further enhanced the differences between CWSI due to N treatment. Non-water-stressed baselines for partial canopies of wheat have not yet been determined and reported.

Jackson et al. (1981) showed that CWSI = $1 - (E/E_p)$, where E is actual evapotranspiration and E_p is potential evapotranspiration. The results of this experiment suggest that when actual evapotranspiration is limited by available water supply to less than 62% of potential evapotranspiration, then increased level of N fertilization increases water stress.

Cumulative evapotranspiration (CET) increased with N application rate up to 56 kg^2 ha^{-1} in 1988, and 28 kg ha^{-1} in 1990 (Table 3). Villalobo and Fereres (1990) showed the strong decline in the ratio of soil evaporation to evapotranspiration that occurs with increasing LAI. Although soil evaporation measurements were not made in the present study, visual observation indicated more rapid soil surface drying in the low-N plots than in the high-N plots. The true increase in evaporative demand and transpiration incurred by the larger plants with greater LAI under high-N rates in this study may be masked by the increased soil evaporation due to the low LAI under low-N rates.

Grain yields increased with N application up to the 84 kg ha^{-1} rate in 1988, and 56 kg ha^{-1} rate in 1990 (Table 3). The year-by-N-treatment interaction was not statistically significant. Averaged over the 2 yr of the study, grain yield increased with increasing N up through the 56 kg ha^{-1} rate. This was a result of increases in LAI, above-ground biomass, and heads per hectare due to increasing N. The decline in yield at the high-N rates was due to insufficient available water to support the greater transpirational demand from the greater LAI. The higher test weights in the low-N treatments are a combination of the lower number of heads per hectare and the lower level of water stress during the milk/dough stages. Water use efficiency increased with N application rate up to 84 kg ha^{-1} in 1988 and up to 56 kg ha^{-1} in 1990 (Table 3). The overall higher WUE in 1990 compared to 1988 may have been a response to precipitation timing. Only 8% (18 mm) of the total growing season precipitation in 1988 occurred during the critical heading and flowering growth stages. In 1990, 39% (79 mm) of the total growing season precipitation occurred during these critical growth stages (Fig. 1, 2).

Grain yield was linearly correlated with cumulative evapotranspiration (Fig. 5). The slopes of the linear regressions for 1988 and 1990 are similar to one reported by Halvorson and Kresge (1982) for winter wheat growing in the Northern Great Plains over a period of 26 yr. This relationship has not been previously reported for this area of the Great Plains. The CET/grain yield/WUE data collected in this study are consistent with those data reported by Hatfield et al. (1988) for winter wheat grown at five locations across the North American Great Plains.

SUMMARY AND CONCLUSIONS

Increased levels of N fertility stimulate both above-ground biomass and root growth. Increased above-ground biomass intercepts more incoming solar irradiance, conferring a higher transpiration requirement on the plant while at the same time making more soil water available through the deeper root system. This gives the potential for greater yields when adequate or moderately limited water is available. However, under conditions of more severe water stress, the larger plant developed during the vegetative growth period may experience increased levels of water stress resulting in lower yields than plants fertilized at a lower N level.

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