No-till Seeded Winter Wheat: Influence of Date of Nitrogen Application on the Grain Yield, Grain Protein, and Yield Components.

A.M. Johnston and D.B. Fowler
Crop Development Centre
University of Saskatchewan

Abstract

An experiment was carried out to determine the influence of date of nitrogen (N) fertilizer application on the grain yield, quality and water use efficiency (WUE) for dry matter and grain yield production of no-till seeded winter wheat. Ammonium nitrate N was surface broadcast either as early as possible in the spring (early), split between 2/3 early and 1/3 at the beginning of stem elongation (split), and 3 weeks after early (late), at rates of 0,34,67,101,134,167, and 202 kg N ha^{-1}. Grain yields ranged from 0.25 to 2.5 t ha^{-1}. High pre-anthesis evaporative demand in 1988 reduced mean grain yield to 0.89 t ha^{-1}, 42% of 1987 yields. While 3 of the 8 trials showed a positive response to N rate, date of N application had no effect on harvest yield and yield components. Grain protein yield and protein concentration were better indicators of N response under these high stress conditions with 6 and 7, respectively, of the 8 trials showing a positive response to N rate. Added N increased water use efficiency of dry matter and grain yield in 5 and 3 of the trials, respectively. Increases in WUE were a reflection of grain and dry matter yield responses to added N and not differences in season long ET. The threshold ET required for zero dry matter and grain yield was 46 and 77 mm, respectively. Forward stepwise regression identified pre-anthesis evaporative demand as the only environmental or soil water parameter influencing harvest dry matter and grain yield response. Dependence of crop response on pre-anthesis evaporation indicates that yield was a function of the atmospheric demand for water in this experiment. Kernels per spike was the yield component that best represented grain yield, explaining 82% of the variation recorded. High evaporative demand during stem elongation reduced the survival of early established tillers and increased the role of kernels per spike, the other pre-anthesis determined yield component, in grain yield formation. Only with the unfertilized check, where pre-anthesis production was reduced due to N deficiencies, did kernel weight have any significant influence in determining grain yield.

Introduction

The development of a practical snow management system, which involves no-till seeding into standing stubble of the previous crop (stubbling-in), has reduced the risk of winterkill and permitted expansion of the winter wheat (Triticum aestivum L.) production area on the Canadian prairies. While no-till seeding maintains the standing stubble necessary to trap an insulating layer of snow during the winter, the recrop environment is usually deficient in plant available nitrogen (N). Correction of this N deficiency is necessary before optimum grain yield and acceptable grain quality can be produced (Fowler et al., 1989a,b).

Winter wheat produced on the Canadian prairies resumes growth in late-April, flowers approximately the third week of June, and is normally harvested in mid-August. The long-term growing season conditions of this region are more moist in May and June, and hot and dry in July (deJong and Steppuhun, 1983). The 32 to 42% yield advantage observed for winter over spring wheat in this region has been attributed to its more efficient early-season water use, and the generally cooler, wetter conditions during the critical booting to flowering development stages (Entz and Fowler, 1990). Therefore, it is important that N fertilizer be positionally available to the winter wheat plant prior to early season demands.

The interaction of N fertilizer additions with environmental and soil water conditions can result in a wide range of crop responses. It has been reported (Peterman, 1983) that the maximum yield potential of winter wheat is established early in the growing season with the number of potential tillers, spikelets per spike, and florets per spikelet determined in a matter of a few weeks in the spring. However, subsequent water, nutrient, and temperature stresses affect the final harvested yield. Consequently, an understanding of the interactions of N fertilizer responses and seasonal environmental stresses is a prerequisite to the development of management packages designed to produce maximum economic yields.

The objective of this study was to determine the influence of date of fertilizer N application on the grain yield, yield components and grain quality of no-till winter wheat grown in Saskatchewan.

Materials and Methods

Eight trials were established in farmer seeded fields of winter wheat (cv. Norstar) in 1987 and 1988 in the Dark Brown and Black soil zones in Saskatchewan (Table 1). Field selection was based on overwinter survival and use of monoammonium phosphate fertilizer seed placed at recommended rates. All nutrients other than N and phosphorus were not considered to be limiting. Soil samples were collected from the plot area for determination of nitrate-N in the early spring of each year following the procedure outlined in the preceding paper (Johnston and Fowler, 1991).

The variables N rate and time of N application were evaluated using a four replicate split-plot experimental design. The N rates used were 0, 34, 67, 101, 134, 167, and 202 kg N ha^{-1} as ammonium nitrate hand broadcast on the surface. The N application times were as early as possible after spring thaw (early), split between 67% early and the remaining 33% at Zadoks growth stage (ZGS) 30 (split) (see Appendix 1 in preceding paper for details on Zadoks growth scale, Johnston and Fowler, 1991), and three weeks after early (late) (Table 1). At the East Sutherland location in 1988 a split-split-plot design was employed with water as the main plot, N rate as the subplot, and time of N application as the sub-subplot. Irrigation water totalling 100 mm was applied in units of 25 mm on May 3 and 16, and June 3 and 16. In the presentation of data this trial was divided into dryland (Trial 7) and irrigated (Trial 8).

Daily minimum and maximum air temperatures, 24 hour rainfall, and soil water were collected as outlined in the preceding paper (Johnston and Fowler, 1991). Evapotranspiration (ET) was calculated from the addition of rainfall to soil water extraction during the season.

Grain yield (90 g H_2O kg^{-1} dry grain) samples were harvested using a small-plot combine, with sample area ranging from 6 to 12 m^2, depending on location. Grain protein concentration (g protein kg^{-1} dry grain) and protein yield (grain yield x protein concentration) were determined for each plot at each trial location. Protein concentrations were determined by the Udy dye method (Udy, 1971), with Kjeldahl analysis used to standardize protein concentration in each trial. At harvest two 1 m rows of crop from each plot were cut at ground level, spike number counted, and then dried to determine total biological yield. The dried samples were threshed and the resulting grain weight used in the calculation of harvest index (HI=grain weight/total biological yield). A subsample of 250 kernels was used to determine kernel weight (mg per kernel). Kernels per spike was calculated by dividing grain weight by kernel weight, the product of which was divided by spike number.

An inverse polynomial equation with a modification for yield depression at high N levels (France and Thornley, 1984) was used to describe the relationship between available N and both grain and grain protein yield. The Gompertz equation was employed to describe the relationship between protein concentration and available N. Use of both of these functions to describe N response curves is outlined in detail by Fowler et al. (1989a,b). The inverse polynomial equation takes the form:

$$Y = \underline{u}N\,(1-N/\underline{s})/(N + \underline{u}/\underline{e}) \qquad [1]$$

where: Y - predicted grain or protein yield (kg ha^{-1})

N - total available N (kg N ha^{-1})

$\underline{s}$ - a measure of yield sensitivity to high N levels (larger $\underline{s}$ indicates less sensitivity)

$\underline{u}$ - upper limit of yield achieved in the absence of sensitivity to high levels of N (kg ha^{-1})

$\underline{e}$ - maximum N use efficiency at low levels of N (kg yield kg^{-1} N)

Table 1. Test location, previous crop, soil characteristics, and time of N fertilizer application for Norstar winter wheat in 1987 and 1988 crop development trials.

Trial	Year	Previous Crop†	Soil: Classification‡	Soil: Texture§	Soil: NO_3-N in early spring (kg ha^{-1})¶	Time of N application (day/month): Early	Split	Late
1. Clair	1986-87	Barley	Yorkton# Black Chernozem	L	29	20/4	20/4:19/5	13/5
2. Hagen	1986-87	Rapeseed	Blaine Lake Black Chernozem	L	40	21/4	21/4:31/5	12/5
3. Kernen	1986-87	Barley	Sutherland Dark Brown Chernozem	C	77	16/4	16/4:29/5	11/5
4. Watrous	1986-87	Barley	Weyburn Dark Brown Chernozem	CL	24	17/4	17/4:29/5	14/5
5. Dafoe	1987-88	Barley	Weyburn Dark Brown Chernozem	L	18	13/4	13/4:25/4	10/5
6. Hagen	1987-88	Rapeseed	Blaine Lake Black Chernozem	L	47	21/4	21/4:26/4	13/5
7&8. East Sutherland	1987-88	Rapeseed	Elstow Dark Brown Chernozem	C	40	14/4	14/4:28/4	11/5

† Barley (Hordeum vulgare L.), Rapeseed (Brassica campestris L.).

‡ Canadian Soil Survey Committee, Subcommittee on Soil Classification, 1978.

§ L-loam, C-clay.

¶ Amount of NO_3-N in the 0 to 60 cm soil layer of unfertilized plots in the spring.

Soils survey report No. 12 (Mitchell, Moss and Clayton, 1944).

Non-linear regression procedures outlined by the SAS Institute (1985) were used to provide least-squares estimates of the regression coefficients $\underline{u}$, $\underline{e}$, and $\underline{s}$. In a few cases, maximum N rates used were too low to allow for reasonable estimates of yield depression at high N rates. In these instances, $\underline{s}$ was held constant at values that provided for minimum yield depression at high N rates (Fowler et al., 1989a,b) and $\underline{u}$ and $\underline{e}$ were successfully estimated.

The Gompertz equation takes the form:

$$P = \underline{M} + \underline{A} \exp [-\underline{B} \exp (-\underline{K}N)] \qquad [2]$$

where: P - predicted protein concentration (g protein kg^{-1} dry grain)

$\underline{M}$ - minimum protein concentration (g protein kg^{-1} dry grain)

$\underline{M} + \underline{A}$ - asymptotic protein concentration achieved at high N levels

$\underline{B}$ - determines N level at which protein concentration reaches $\underline{M} + 0.5\underline{A}$

$\underline{K}$ - coefficient that determines the rate P increases to $\underline{M} + \underline{A}$

N - total available N (kg ha^{-1})

The coefficients $\underline{K}$ and $\underline{M}$ were held constant at 0.0230 and 95.4, respectively (Fowler et al., 1989b). Non-linear regression procedures outlined by the SAS Institute (1985) were used to provide least squares estimates of the coefficients $\underline{A}$ and $\underline{B}$.

Simple correlations were used to determine the relationship among and between variables measured. Forward stepwise regression analysis (SAS Institute, 1985) was used to determine those factors which had the greatest influence on the response of dependent variables.

Results and Discussion

Environmental Conditions

As outlined in the preceding paper (Johnston and Fowler, 1991) above average air temperatures and below average rainfall were recorded in May and June of 1987 and 1988. The early season growth and demand for water, characteristic of winter cereals, was negatively influenced by these conditions. The resulting dry matter and grain yield responses reflect those of high stress growing conditions for Saskatchewan.

Grain and Protein Yield and Protein Concentration

The inverse polynomial equation (Eq.[1]) outlined by France and Thornley (1984) provided an excellent description of the grain and grain protein yield responses to N fertilization (Fig. 1; Table 2). Average reduction in sums of squares due to model was 97% and 98% for grain and grain protein yield, respectively. Grain yields recorded in this experiment ranged from a low of 0.25 t ha^{-1} in Trial 5, to a high of 2.5 t ha^{-1} in Trials 1 and 4 (Fig. 1; Table 2). Mean grain yield was 2.13 t ha^{-1} for 1987 and 0.89 t ha^{-1} for 1988, considerably less than the long-term average winter wheat grain yield of 2.7 t ha^{-1} for properly managed fields in Saskatchewan (Fowler, 1983). Increasing N rate significantly ($P<0.05$) increased grain yield in Trials 1,2, and 4. The absence of a grain yield response to added fertilizer N was due to high soil residual nitrate-N (77 kg N ha^{-1}) in Trial 3 (Table 1), and the high pre-anthesis temperature stress conditions during stem elongation recorded for Trials 5 to 8 in 1988. While grain yield declines were recorded with increasing N rate in several of the trials in both 1987 and 1988, these declines were never significant ($P>0.05$).

Grain protein yield and grain protein concentration proved to be better indicators of N response with six and seven, respectively, of the eight trials showing significant ($P<0.05$) increases with added fertilizer N (Fig. 1). While environmental conditions limited the grain yield response, N treatments increased grain protein concentration and the corresponding grain protein yield. The absence of grain yield, protein yield, and protein concentration responses in Trial 7 indicates that environmental conditions prevented the movement of fertilizer N into the soil and uptake by the crop.

The Gompertz equation (Eq.[2]) provided an excellent description of the grain protein concentration and total available N relationship (Fig. 1). Average reduction in sums of squares due to model was 99%. Maximum protein concentration values ranged from a low of 116 g kg^{-1} in Trial 3,

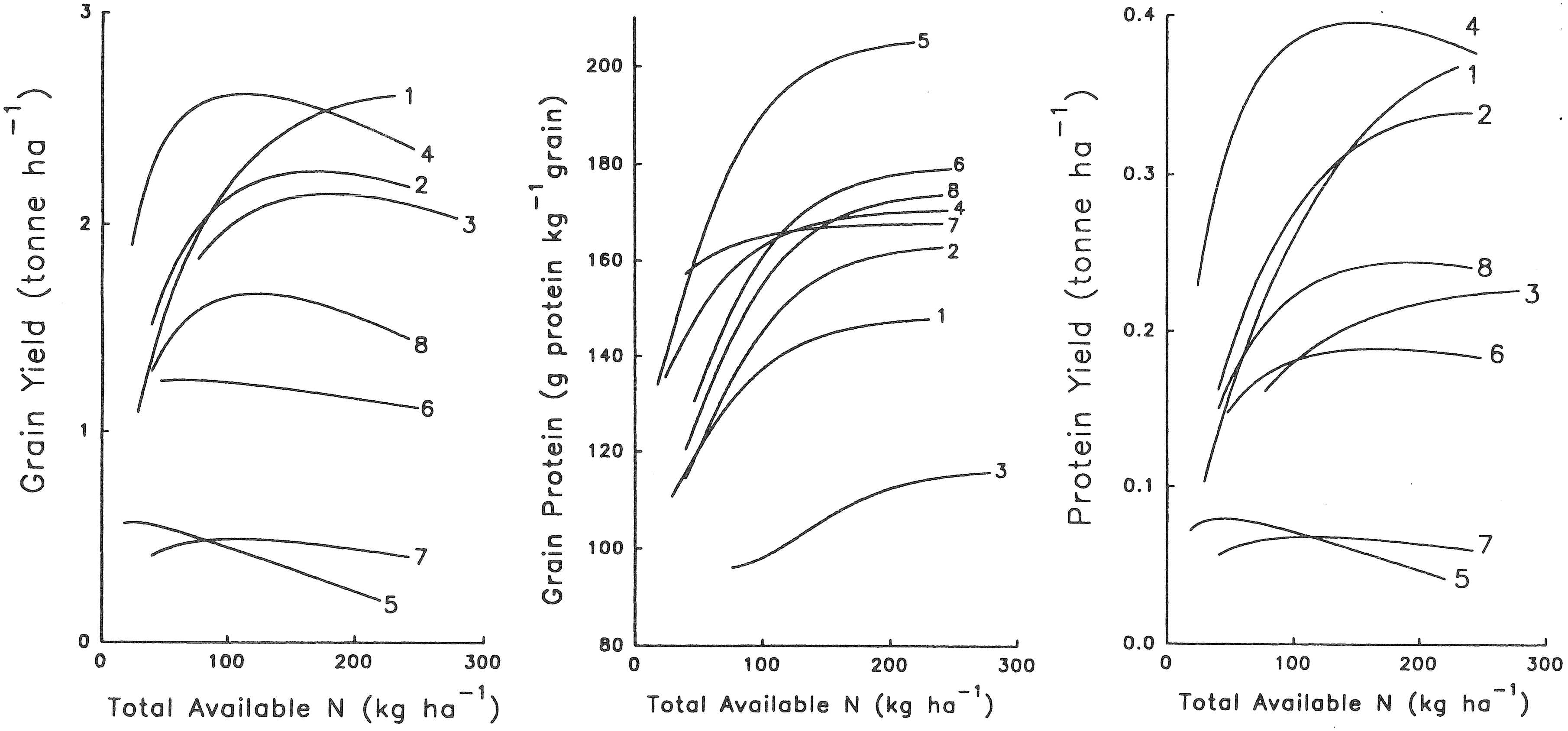

Figure 1. Grain and protein yield and grain protein concentration for Norstar winter wheat at 1987 and 1988 crop development trials. See Table 1 for details on individual trials. See Table 2 for regression equations.

Table 2. Estimated regression coefficients for no-till winter wheat grain yield (Eq.[1]), grain protein yield (Eq.[1]), and grain protein concentration (Eq.[2]) to early spring broadcast ammonium nitrate N fertilizer at crop development trials. See Table 1 for details on trial locations.

Trial†	u‡	e§	s¶	r^2
	---Grain Yield---			
1	4318(1231)#	52(8.7)	1296(1145)	.99
2	3603(260)	71(12.3)	903	.99
3	3587(303)	59(13)	903	.99
4	3495(367)	184(84)	903	.98
5	682(235)	281(1038)	311(99)	.94
6	1380(411)	408(1782)	1375(1877)	.99
7	764(988)	26(60)	599(1083)	.90
8	2717(90)	70(3)	638(30)	.99
	---Grain Protein Yield---			
1	998(163)	4.1(.40)	949	.99
2	684(44)	5.6(.40)	949	.99
3	339(213)	4.3(2.3)	1925(4674)	.99
4	581(60)	16.4(4.9)	949	.99
5	104(36)	15.7(24)	373(150)	.95
6	270(115)	7.5(4.9)	1110(1358)	.99
7	101(109)	3.7(7.5)	711(1390)	.93
8	410(36)	6.3(1.1)	949	.99

	A††	B‡‡		r^2
	---Grain Protein Concentration---			
1	53.1(4.7)	2.41(.85)		.97
2	68.3(1.3)	3.2(.25)		.99
3	21.1(1.75)	20.7(5.5)		.98
4	75.4(2.5)	1.1(.20)		.99
5	110.7(3.8)	1.6(.24)		.99
6	84.4(3.7)	2.6(.53)		.99
7	72.5(5.4)	0.4(.50)		.98
8	79.2(0.6)	2.9(.01)		.99

†See Table 1 for details on individual trial locations.

‡u - Upper limit of yield achieved in the absence of sensitivity to high levels of N (kg ha^{-1}).

§e - Maximum N use efficiency at low levels of N (kg yield kg^{-1} N).

¶s - Measure of yield sensitivity to high N levels.

- value in brackets is standard error of the estimate.

††A - Asymptotic protein concentration.

‡‡B - determines N level at which protein concentration reaches M + 0.5A (M - minimum protein concentration).

to a high of 207 g kg^{-1} in Trial 5. While the highest protein concentration in Trial 5 corresponds with the lowest grain yield, the low grain protein concentration in Trial 3 was not a reflection of high grain yields. Trial 3 was characterized by below average (63%) April to June rainfall and high spring residual nitrate-N (77 kg N ha^{-1}). Under these dry early spring conditions very little of the applied fertilizer N was recovered by the crop. It would appear from the absence of any difference between early, split or late-N that high evaporative demand from high air temperatures either prevented late season uptake of N by rapidly senescing plants, or redistribution of N from the above ground dry matter during grain filling (Campbell et al., 1977).

Forward stepwise regression (SAS Institute, 1985) was used to identify those environmental and soil water conditions having the greatest influence on grain yield, protein yield, and grain protein concentration. The environmental parameters considered were mean daily growing degree days (GDD), pan evaporation (E), and rainfall (R) during growth periods (GP) 1 (ZGS21-30), GP2 (ZGS32-65), GP3 (ZGS65-85), and GP4 (ZGS85-92). Extractable soil water in both the root zone and the 110 cm profile at the beginning of elongation (ZGS30), at anthesis (ZGS65), and at soft dough (ZGS85) were also included in the regression model.

Pan evaporation during stem elongation (GP2) was the only factor that significantly ($P<0.05$) influenced both grain and protein yield responses for the trials in this experiment (Table 3). These results support the findings of Entz and Fowler (1988), who reported that pan evaporation in the period immediately prior to anthesis was the single most important factor influencing both grain and grain protein yield. The influence of pre-anthesis evaporation (E2) on both grain and grain protein yield, as well as harvest dry matter yield (Table 3), leads to the conclusion that evaporative demand during the pre-anthesis stem elongation period restricted crop production potential in these trials. The absence of an influence of rainfall or soil water in the regression models indicates that the demand for water was more important than the supply of water for both dry matter and grain yield production

Table 3. Regression of climatic and extractable soil water variables on agronomic characters measured in 1987 and 1988 crop development trials. (n=8).

Equation		r^2
1	Grain Yield = 4429 - E2† (274)	0.82^{**}
2a	Grain Protein = 10.28 + RZE (0.17)	0.69^{*}
2b	= 7.24 + E2 (0.37) + RZE (0.14)	0.88^{**}
3	Grain Protein Yield = 581.7 - E2 (34.5)	0.69^{*}
4	Harvest Dry Matter = 8945 - E2 (476)	0.82^{**}
5	Post-anthesis Dry Matter = 5778 - E2 (375)	0.75^{**}
6	Kernels $Spike^{-1}$ = 31.09 - E2 (1.43)	0.51^{*}
7	Spikes m^{-2} = 617 - E2 (30.3)	0.76^{**}
8	Harvest Index = 0.78 - E4 (0.06)	0.85^{**}

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

† E2 - Class A pan evaporation during GP2 (ZGS30-65), E4 - Class A pan evaporation during GP4 (ZGS85-92), RZE - Extractable soil water - root zone at elongation.

(Entz and Fowler, 1988).

Grain protein concentration was most dependent on available soil water in the root zone (30 cm) at elongation (RZE) (Table 3). The addition of E2 to the stepwise regression equation for protein concentration improved predictability, reflecting the dependence of protein concentration on grain yield production. Increased E2 reduced grain yield and increased grain protein concentration, supporting the accumulated evidence of an inverse relationship between grain yield and protein concentration (Fernandez and Laird, 1959; Terman et al., 1969; Campbell et al., 1981). A positive influence of available soil water at elongation (RZE) on protein concentration was also reflected in a significant ($P<0.05$) positive correlation between grain protein concentration and RZE ($r=0.83^*$). However, negative correlations were recorded between available soil water in the profile at elongation (PE) and grain protein ($r=-0.75^*$), and between RZE and PE ($r=-0.83^*$). These responses indicate that a greater proportion of the soil profile (110 cm) available water at elongation was in the root zone for trials that had high grain protein concentration. This variation in the grain protein concentration response between root zone and profile available soil water at elongation, indicates limited rooting zone (30 cm) of the crop at this stage of growth, and does not reflect future crop water requirements.

Yield Components

Spike number, kernels per spike, and kernel weight are presented for the crop development trials in Table 4. The significant ($P<0.01$) increase in kernel weight with added N in Trial 5 and 6 was associated with a nonsignificant ($P>0.05$) reduction in kernels per spike. This reflects the high pre-anthesis evaporative demand that restricted kernel formation in these 1988 trials. Forward stepwise regression analysis was used to determine the influence of environmental conditions on yield components. Pan evaporation during stem elongation (E2) was the single most important environmental factor influencing spike number and kernels per spike (Table 3). None of the environmental or soil water parameters explained the variation in kernel weight. This common response for both yield components and grain yield to E2 again reflects the importance of pre-anthesis growing conditions on yield formation (Shanahan et al., 1984; Entz and Fowler, 1988).

Forward stepwise regression analysis was also used to determine the influence of individual yield components on grain yield. Kernels per spike was found to be the dominant yield component when the trial mean responses for grain yield and yield components were considered for all eight trials (Table 5). Increased pan evaporation and accumulation of GDD (with high air temperatures) during stem elongation reduced the number of days prior to anthesis by 33% in 1988 compared to 1987. This shortened pre-anthesis period inhibited tiller establishment, reducing 1988 spike number by 30% and increasing the role of kernels per spike in determining grain yield. Kernel weight showed no influence on grain yield when considered across environments.

Data for the unfertilized check, early, split, and late-N application dates (Trials 1,2, and 4) were considered to determine the influence of yield components on grain yield (Table 5). Spike number accounted for 46% of the variation in grain yield of early-N treatments. With split and late-N timing both spike number and kernels per spike were required to produce a significant ($P<0.05$) reduction in grain yield sum of squares. As discussed in the preceding paper (Johnston and Fowler, 1991), the promotion of primary tiller emergence with early-N timing increases the role of spike number in determining grain yield (Fraser and Dougherty, 1977; Mclaren, 1981; Darwinkel, 1983). Kernel weight was the dominant yield component influencing grain yield for the unfertilized check treatments (Table 5). This strong influence of kernel weight indicates the increased importance of post-anthesis grain filling on yield response under N deficient conditions where spike size and tillering are restricted.

Table 4. Spikes m^{-2}, kernels $spike^{-1}$, and kernel weight for 1987 and 1988 crop development trials.

Trial†		1	2	3	4	5	6	7	8
		Spikes m^{-2}							
N Rate	0	269	234	339	341	207	269	192	295
(kg ha^{-1})	34	367	299	329	421	254	320	233	NI‡
	67	442	314	306	412	214	305	191	326
	101	424	302	327	420	194	263	217	NI
	134	422	326	360	401	201	276	210	281
	168	433	344	344	450	196	262	175	NI
	202	402	336	342	461	182	308	230	360
	SE	30.2**	19.0**	20.6	35.7*	40.6	15.4**	43.4	28.1
N Time	Early§	415	299	337	426	200	286	201	317
	Split	392	315	326	440	218	286	211	307
	Late	376	309	342	379	202	286	205	324
	SE	31.0	19.4	19.1	37.7	20.6	15.3	12.5	16.9
		Kernels $spike^{-1}$							
N Rate	0	14.9	21.5	17.5	16.8	9.7	16.9	5.1	15.7
(kg ha^{-1})	34	17.0	21.0	18.4	19.3	9.6	13.4	11.6	NI
	67	16.4	20.6	20.0	18.3	6.7	15.1	5.7	20.0
	101	17.3	23.2	20.0	20.1	7.7	15.2	9.2	NI
	134	18.6	21.6	18.0	21.4	6.0	14.5	9.0	19.7
	168	18.5	21.6	18.1	19.9	6.2	14.4	5.5	NI
	202	21.1	22.2	19.1	17.6	7.2	14.0	8.2	18.1
	SE	1.5*	1.3	1.3	1.9	1.9	1.4	2.9	2.1
N Time	Early	17.5	22.1	19.2	19.7	7.2	14.9	7.3	18.9
	Split	17.8	21.1	18.5	17.9	7.3	14.6	8.1	18.9
	Late	17.6	21.8	18.5	19.5	8.2	14.8	7.9	17.4
	SE	1.3	1.5	1.7	1.1	0.9	0.9	1.7	1.0
		Kernel weight (mg $kernel^{-1}$)							
N Rate	0	28.1	31.6	32.3	30.0	27.1	28.0	29.1	26.6
(kg ha^{-1})	34	28.5	32.1	32.9	30.0	28.8	28.4	26.5	NI
	67	30.1	32.1	32.3	30.8	28.9	28.7	28.9	25.2
	101	31.2	31.5	32.8	29.9	30.0	28.4	27.8	NI
	134	30.6	30.7	32.9	30.0	30.1	29.4	27.9	26.1
	168	31.9	31.5	32.2	29.3	30.3	29.2	29.4	NI
	202	31.0	31.5	32.8	29.8	30.7	29.4	27.1	24.9
	SE	0.5**	0.5	0.5	0.5	0.6**	0.4*	1.5	0.7
N Time	Early	29.9	31.9	32.5	29.6	29.2	28.7	28.4	25.7
	Split	29.7	31.4	32.7	29.8	29.0	28.8	28.2	25.5
	Late	31.0	31.4	32.7	30.5	30.0	28.8	28.1	25.8
	SE	1.2	0.6	1.0	0.8	0.3	0.2	0.4	0.4

*,** Significant at the 0.05 and 0.01 levels of probability, respectively.

† Trial location - See Table 1 for details on individual trials.

‡ NI - N rate not included at this trial.

§ N application time, see Table 1 for details.

Water Use Efficiency

Mean season long water use efficiency of dry matter (WUEDM) in 1987 was 18.8 kg DM ha^{-1} mm^{-1} ET, with similar pre- and post-anthesis WUEDM values of 19.5 and 18.2 kg DM ha^{-1} mm^{-1} ET, respectively (Table 6). In research conducted across the Great Plains region the season long WUEDM for well fertilized rain-fed winter wheat ranged from 12 to 24 kg ha^{-1} mm^{-1} ET (Hatfield et al., 1988). Entz and Fowler (1989) reported higher season long WUEDM values of 27.1 kg DM ha^{-1} mm^{-1} ET, respectively, for winter wheat in Saskatchewan. The season long mean WUEDM of 17.9 kg DM ha^{-1} mm^{-1} ET in 1988 was similar to that observed in 1987. However, in 1988 the pre-anthesis WUEDM was 22.5 kg DM ha^{-1} mm^{-1} ET, almost twice that of the post-anthesis WUEDM of 13.3 kg DM ha^{-1} mm^{-1} ET. High pre-anthesis evaporative demand, and the absence of post-anthesis rainfall in 1988 restricted the accumulation of dry matter, reducing WUEDM. The significant ($P < 0.05$) WUEDM responses were primarily due to the influence of N rate on dry matter accumulation (Johnston and Fowler, 1991). This agrees with the hypothesis of Viets (1962) that N induced increases in WUE were the result of increased biomass or grain production and not an effect of N rate on ET.

Table 5. Stepwise regression of yield components on grain yield (GY) in 1987 and 1988 crop development trails.

		r^2
All†	GY = -560.02 + KS‡ (131.80)	.86**
	GY = -1134.55 + SM2 (4.21) + KS (89.04)	.99**
N treatment§		
Check	GY = -2456.02 + KW (130.60)	.47**
	= -4436.86 + SM2 (3.77) + KW (161.38)	.84**
	= -1952.25 + SM2 (5.71) + KS (97.47) + KW (2.34)	.99**
Early	GY = 1270.66 + SM2 (2.68)	.46**
	= -2149.01 + SM2 (5.16) + KS (122.26)	.87**
	= -4161.15 + SM2 (5.66) + KS (116.74) + KW (63.07)	.94**
Split	GY = 1416.72 + SM2 (2.27)	.21^{NS}
	= -2128.22 + SM2 (5.42) + KS (119.18)	.80**
Late	GY = 1475.46 + KS (37.77)	.19^{NS}
	= -2026.42 + SM2 (5.64) + KS (108.94)	.87**
	= -4767.38 + SM2 (6.21) + KS (112.46) + KW (79.06)	.95**

†All - represents the trial mean response for all eight trials (n=8). See Table 1 for details on individual trials.

‡KS - kernels spike^{-1}, SM2 - spikes m^{-2}, KW - kernel weight.

§N treatments - mean response for unfertilized check (n=9) and N application times (n=18).IN trials where a significant N rate response was recorded (Trials 1,2,4). See Table 1 for details on N application times.

The water use efficiency for grain yield (WUEGYLD) ranged from a low of 3.8 kg ha^{-1} mm^{-1} ET in Trial 5 to a high of 13.1 kg ha^{-1} mm^{-1} ET in Trial 3 (Table 6). These WUEGYLD values are lower than the 7.6 to 13.9 kg ha^{-1} mm^{-1} ET reported for Norstar winter wheat by Entz (1988) during the period from 1985 to 1986 in Saskatchewan. The low WUEGYLD in Trial 5 and 7 were a reflection of the low grain yields in these trials ($<$500 kg ha^{-1}). Increased N rate significantly ($P<0.05$) increased WUEGYLD in Trials 1,2, and 4, a reflection of the grain yield responses to N fertilization (Fig. 1). As observed for the WUEDM responses, it was an increase in grain yield accompanied by little or no effect on ET that produced the N induced increase in efficiency of water utilization in these trials. The addition of 100 mm of irrigation water in Trial 8 increased mean dry matter (Johnston and Fowler, 1991) and grain yield (Fig. 1) by 212 and 130 %, respectively, over those recorded in the dryland Trial 7. The WUEDM and WUEGYLD for Trials 8 compared to Trial 7 were also increased by 36 and 98 %, respectively (Table 6). These results contradict those of Steiner et al. (1985) and Entz and Fowler (1989), who reported no difference between irrigated and dryland WUEDM and WUEGYLD. This data indicates an increased response for both aerial dry matter and grain yield relative to that of ET. One possible explanation is that the additional irrigation water helped to alleviate some of the negative effects recorded from high pre-anthesis evaporative demand, thereby improving the crop response recorded in Trial 8 (irrigated) over that in Trial 7 (dryland).

Table 6. Water use efficiency of harvest dry matter and grain yield for 1987 and 1988 crop development trials.

Trial	1†	2	3	4	5	6	7	8
Dry Matter	----------kg ha^{-1} mm^{-1}----------							
Check	13.6	11.5	22.0	12.7	14.2	16.6	15.1	19.1
Early‡	21.9	14.7	22.7	16.2	17.2	18.2	15.0	21.7
Split	21.1	15.2	21.6	17.7	18.0	19.1	14.9	20.6
Late	20.7	14.8	21.8	14.4	17.8	19.2	14.6	19.7
SE	1.5*§	0.9*	2.2	1.4*	1.4*	1.5	2.9	1.8*
Grain Yield	----------kg ha^{-1} mm^{-1}----------							
Check	5.8	5.9	13.1	8.2	5.1	8.9	3.9	7.9
Early	9.3	7.6	12.9	11.0	3.8	8.3	4.2	8.9
Split	9.9	7.3	12.8	10.1	4.4	8.3	4.2	8.4
Late	9.2	7.4	13.1	9.7	4.0	8.0	4.4	8.0
SE	0.7*	0.3*	0.6	0.8*	1.0	0.4	1.6	0.8

† See Table 1 for details on individual trial locations.
‡ Time of N application - see Table 1 for details on N application timing at each trial.
§ Standard error for N rate response. * - Significant ($P=0.05$) F test response for N rate.

The relationship between grain yield, harvest dry matter yield, and ET are shown in Figure 2. There was a linear relationship over the wide range of grain and dry matter yields recorded. Extrapolation of the linear relationship between grain and harvest dry matter yield indicated that 996 kg ha^{-1} of biomass were required before any harvestable grain yield was produced.

The mean HI for this experiment was .40. A significant ($P<0.01$) correlation was recorded between HI and ET ($r=0.84^{**}$). This positive relationship between ET and HI indicates that the ability of the winter wheat crop to translocate accumulated biomass into grain yield was a function of the crop water use. Regression equations indicate that the threshold level of ET required for zero yield was 77 and 46 mm for grain and dry matter, respectively (Fig. 2). These threshold grain and dry matter yield values are almost identical to the 78 and 51 mm ET, respectively, reported by Hatfield et al. (1988) indicating a consistent pattern of grain and dry matter yield response to ET for winter wheat produced on the North American Great Plains.

While correlations between available soil water in the 110 cm profile at spring green-up and grain

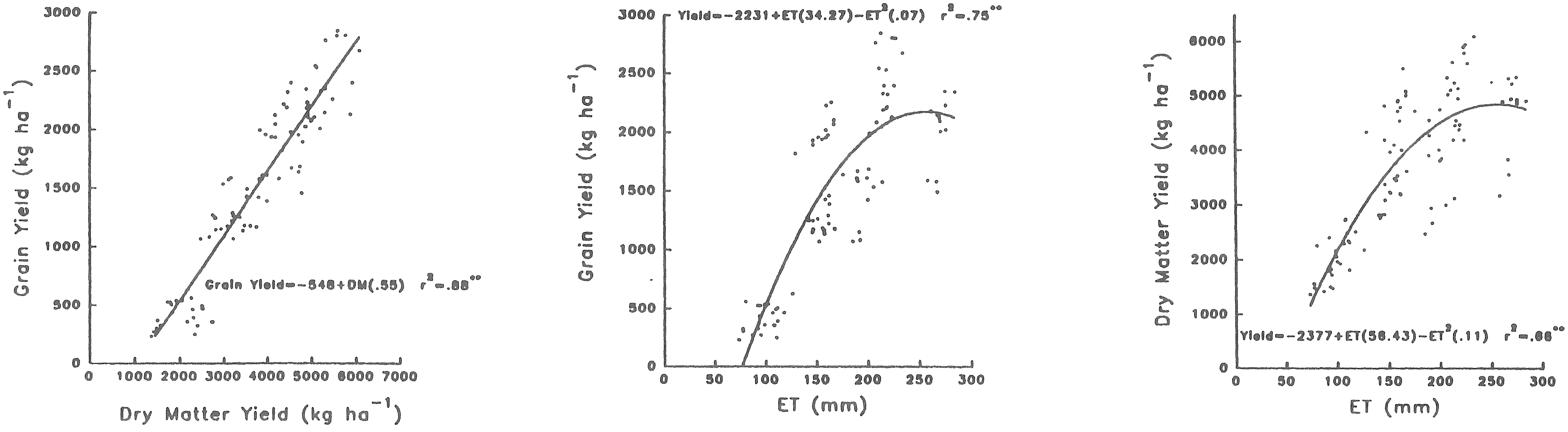

Figure 2. Relationship between grain and dry matter yield and season long ET for 1987 and 1988 crop development trials. Points represent trial mean N rate by N time response (n=96).

yield were not significant ($P > 0.05$), a strong positive relationship was recorded between post-anthesis ET and grain yield ($r=0.89^{**}$). Post-anthesis ET was also positively associated with post-anthesis rainfall ($r=0.91^{**}$) and season long ET ($r=0.94^{**}$). The close association between post-anthesis growing conditions and yield were a result of the high 1987 grain yields and post-anthesis rainfall compared to the low grain yield and rainfall in 1988 (Table 2, Johnston and Fowler, 1991).

Summary and Conclusions

The variable growing season weather conditions experienced in semiarid climates like that of the Canadian prairies have a large influence on no-till recrop winter wheat growth and yield response to N fertilization. Growing season environmental conditions and plant-available-N levels also play an important role in determining the efficiencies of N translocation to the seed.

The high air temperatures recorded during stem elongation in 1988 resulted in pre-anthesis evaporative demand being the single most important factor influencing plant development and yield in this experiment. The high evaporative demand shortened the 1988 growing season to 60 days from the 91 days recorded in 1987. Grain yields were reduced in 1988 to 42% of those recorded in 1987.

Stepwise regression identified mean daily pan evaporation during stem elongation as the only environmental or soil water factor influencing both grain and dry matter yields. The lack of response to differences in available soil water indicates that grain and dry matter yield were a function of the aerial environment with recrop winter wheat in this experiment. The threshold water required for the production of any grain (77 mm) or dry matter (46 mm) yield in these trials was similar to that recorded in previous Great Plains studies indicating considerable stability in the response of winter wheat across a wide range of environments and latitudes. Increased water use efficiency of both dry matter and grain yield following N fertilization was the result of increased dry matter and grain yields and not changes in ET.

Kernels per spike was the yield component that had the largest influence on grain yield response in this study. High evaporative demand during stem elongation reduced the survival of early established tillers, thereby increasing the role of kernels per spike in grain yield formation. Only in the unfertilized check, where pre-anthesis tiller production was reduced due to N deficiencies, did kernel weight have a significant influence on grain yield. These results clearly indicate that, under the recrop conditions used in the production of winter wheat, the pre-anthesis establishment of tillers and kernels per spike is critical to the achievement of high grain yields.

Acknowledgements

This research was funded by the Canada-Saskatchewan Economic Regional Development Agreement grant. Financial support in the form of postgraduate scholarships to the senior author from the Canadian Wheat Board, College of Agriculture (Knowles Postgraduate Scholarship), and the College of Graduate Studies and Research is gratefully acknowledged.

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