OPTIMIZING NITROGEN FERTILIZER RESPONSE BY WINTER WHEAT AND RYE

D.B. Fowler, J. Brydon and R.J. Baker

Crop Development Centre

University of Saskatchewan

Saskatoon, Saskatchewan

Abstract

Southwestern Alberta has been the traditional winter wheat production area in western Canada. In recent years, the adoption of a practical snow management system, which utilizes no-till seeding into standing stubble immediately after harvest of the previous crop, has resulted in an extension of this production area to include most of the western Canadian prairies. Winter rye is also adapted to the no-till production system developed for winter wheat. Most stubble fields are deficient in available soil nitrogen (N) with the result that N fertilizer is a major input cost in the production of no-till winter wheat and rye. This report summarizes the N response observed in 40 winter wheat and 20 winter rye trials representing a broad range of soil types and environments in western Canada.

N fertilizer did not have a significant influence on heading date, maturity, hectoliter weight or kernel size in most trials. Where a significant N response was detected, maximum differences were a one and two day delay in heading, a two and nine day delay in maturity, a three and three kg reduction in hectoliter weight, and a seven and nine mg

reduction in seed size for wheat and rye, respectively. A significant N response was observed more frequently for height. In this instance, the response was not directional and increases up to 25 and eight cm and reductions to nine and nine cm were observed with increased N for wheat and rye, respectively.

The Gompertz equation provided the most complete description of the relationship between protein concentration and total plant-available N. Predicted grain protein concentration from this equation explained 98 and 93 percent of the variability in actual grain protein concentration for wheat and rye, respectively. The N response curves for protein concentration were similar for winter wheat and rye. After an initial lag, protein concentration increased rapidly, and then tailed off at high N levels.

An inverse polynomial function was employed to describe grain and protein yield response to N fertilizer. Predicted yields from these equations explained 96 and 88 percent of the variability in actual grain yield and 94 and 89 percent of the variability in actual protein yield for wheat and rye, respectively. Winter rye demonstrated a greater N use efficiency and yield potential than winter wheat. There was a large interdependence of N response and environmental conditions, especially moisture supply, in determining yield in these trials.

INTRODUCTION

The traditional winter wheat production area in western Canada has been southwestern Alberta. Warm chinook winds in this region moderate winter temperatures and reduce the risk of winterkill to an acceptable level for winter wheat production. Many attempts have been made to produce winter wheat on the remainder of the prairies; but, the frequency of winterkill with conventional production methods, i.e. seeding into a tilled seedbed, prevented its establishment as a viable crop option outside of the chinook region.

The absence of significant progress in the development of super-hardy winter wheat cultivars (Fowler et al. 1983) has resulted in research efforts being directed toward the development of production systems that would allow winter wheat to avoid the worst winter stresses. A practical snow management system, which utilizes direct seeding into standing stubble immediately after harvest of the previous crop (no-till or stubbling-in), has shown the most promise for expanding winter wheat production area in western Canada (Fowler 1983). The success of the management system is best demonstrated by the increase in Saskatchewan's winter wheat production from less than 1000 ha harvested in 1973 to 340,000 and 327,000 ha harvested in 1985 and 1986, respectively. The potential for no-till winter wheat is further emphasized when one considers that winters as severe as the one experienced in 1984-85 are expected to occur only once in 30 to 50 years in this region (Fowler and Entz 1986).

Nitrogen (N) fertilizer is the major input cost in the production of no-till winter wheat in western Canada (Fowler and Entz 1986). Most stubble fields are deficient in available soil N and in high production environments it is common to find soil test results that indicate less than 30 kg ha^{-1} available N. Consequently, responses to N fertilization are usually very dramatic.

Winter rye production in western Canada has traditionally been confined to lighter, less productive soils where erosion and late summer drought are problems. The risks associated with production on these soils are high and there has not been a large incentive to add extra costs in the form of fertilizers. Winter rye is also adapted to the no-till production system developed for winter wheat. As is the case with winter wheat, no-till winter rye usually requires N fertilization to maximize yields.

Cereal protein contains approximately 17.5 percent nitrogen (N). This N is obtained from the soil, and therefore, plant-available soil N has a direct influence on grain protein yield. Most stubble fields are deficient in soil N with the result that grain protein concentrations for no-till winter cereals have been very low, often less than 10 percent (Fowler 1983). Low protein concentrations in winter wheat are usually reflected by "piebald", "yellow berry" or "starchy" kernels. Protein concentrations of greater than 11 percent are preferred for the hard red winter wheat market class, and therefore, if the frequency of piebald kernels is high a sample will be degraded. Consequently, correcting a soil N deficiency usually means extra returns to the producer from both higher yield and better grade (Fowler 1983).

The importance of eliminating N deficiencies in no-till or "stubbled-in" winter cereal production are easily demonstrated. However, characterizing the responses to N fertilization has been more difficult, largely because of a limited data base. This report summarizes data from 40 replicated field trials in which the effect of N fertilization on winter wheat and rye heading date, grain maturity, grain yield, protein concentration, protein yield, hectoliter weight and 1000-kernel weight was measured.

MATERIALS AND METHODS:

A total of 40 fertilizer trials were conducted during the period 1974 to 1986. Trial sites were located throughout all but the southwest corner of the agricultural region of Saskatchewan. This provided nitrogen (N) response data for 40 winter wheat and 20 winter rye site-years representing a broad range of soil types and environmental conditions (Tale 1). The most highly adapted winter wheat and rye cultivars for this region were utilized in these trials. As additional date and new releases become available this resulted in several cultivar changes (Table 1 and 2). The two winter wheat cultivars, 'Sundance' and 'Norstar' have similar grain protein concentrations and yields (Fowler and de la Roche 1984). The winter rye cultivars, 'Frontier', 'Cougar', and 'Puma', have relative grain yields of 84, 90 and 100 percent and grain protein concentrations of 10.5, 9.7 and 8.8 percent, respectively. Protein yields for the rye cultivars were similar.

Experimental design for trials that included both winter wheat and rye was a split plot with species the main plots and N rates the sub-plots. Experimental design for trials that included only winter wheat was a randomized complete block. N treatments were replicated from 3 to 12 times in each trial. With two exceptions (Table 1), trials were direct seeded into standing stubble immediately after harvest of the previous crop (no-till or stubbling-in). Trials were seeded with a small plot hoe-press drill or a commercial minimum tillage drill. Each fertilizer plot was 5.5 m long and 1.2 m wide. Seeding date was between 24 Aug. and 7 Sept. of each year. Phosphate fertilizer (11-55-0 or 11-48-0) was applied with the seed at rates recommended for each soil type. Other elements were not considered limiting. Available N estimates for each

Table 1. Cropping information, cultivar and environment descriptions for 40 winter wheat and 20 winter rye fertilizer trial sites in Saskatchewan, 1974-86.

			Soil				Cultivar Utilized		
Location	Year	Previous Crop[†]	Classification[‡]	Series	Texture[‡]	Spring Available Nitrogen (kg/ha)[§]	Wheat	Rye	Environmental Conditions[¶]
1. Clair	1974-75	Summerfallow	Black	Yorkton	L	117	'Sundance'	'Frontier'	Average
2. Clair	1975-76	Rapeseed	Black	Yorkton	L	29	Sundance	'Cougar'	Average
3. Clair	1976-77	Rapeseed	Black	Yorkton	L	24	Sundance	Cougar	Average
4. Clair	1976-77	Rapeseed	Black	Yorkton	L	54	Sundance	Cougar	Good#
5. Clair	1976-77	Rapeseed	Black	Yorkton	L	24	Sundance	Cougar	Average
6. Saskatoon	1976-77	Rapeseed	Dark Brown	Sutherland	SiCL	220	Sundance	Cougar	Average[††]
7. Saskatoon	1976-77	Rapeseed	Dark Brown	Sutherland	SiCL	220	Sundance	Cougar	Poor
8. Clair	1977-78	Barley	Black	Yorkton	L	19	Sundance	Cougar	Good
9. Clair	1977-78	Barley	Black	Yorkton	L	47	Sundance	Cougar	Good
10. Saltcoats	1981-82	Barley	Black	Yorkton	L	79	'Norstar'	'Puma'	Average
11. Kipling	1981-82	Winter wheat	Dark Brown	Weyburn	L	47	Nortar	Puma	Poor
12. Saskatoon	1977-78	Rapeseed	Dark Brown	Sutherland	SiCL	65	Sundance	Cougar	Poor
13. Langbank	1981-82	Winter wheat	Dark Brown	Weyburn	L	28	Norstar	Puma	Poor
14. Carnduff	1981-82	Durum wheat	Black	Oxbow	L	62	Norstar	Puma	Poor
15. Saskatoon	1981-82	Barley	Dark Brown	Sutherland	HC	125	Norstar	Puma	Good[††]
16. Wynyard	1981-82	Spring wheat	Black	Oxbow	L	57	Norstar	Puma	Good
17. Clair	1982-83	Winter wheat	Black	Yorkton	L	43	Norstar		Average[‡]
18. Kindersley	1982-83	Winter wheat	Brown	Sceptre	CL	47	Norstar		Poor
19. Watrous	1982-83	Winter wheat	Dark Brown	Weyburn	L	33	Norsar		Average[‡]
20. Meadow Lake	1982-83	Rapeseed	Black	Meadow Lake	C	29	Norstar	Puma	Poor
21. Kelvington	1982-83	Barley	Black	Yorkton	L	155	Norstar	Puma	Average
22. Nipawin	1982-83	Rapeseed	Dark Gray	Shellbrook	FSL	39	Norstar	Puma	Average
23. Paddockwood	1982-83	Rapeseed	Dark Gray	Pelly	L	71	Norstar	Puma	Average
24. Outlook	1983-84	Rapeseed	Dark Brown	Bradwell	FSCL	111	Norstar		Irrigation
25. Clair	1983-84	Barley	Black	Yorkton	L	29	Norstar		Good
26. Clair	1983-84	Rapeseed	Black	Yorkton	L	22	Norstar		Good
27. Paddockwood	1983-84	Rapeseed	Dark Gray	Paddockwood	L	36	Norstar		Good
28. Saskatoon	1983-84	Rapeseed	Dark Brown	Sutherland	C	103	Norstar		Poor
29. Saskatoon	1983-84	Rapeseed	Dark Brown	Sutherland	C	103	Norstar		Poor
30. Strasbourg	1983-84	Winter wheat	Dark Brown	Weyburn	L	19	Norstar		Poor
31. Watrous	1983-84	Winter wheat	Dark Brown	Weyburn	CL	33	Norstar		Poor
32. Outlook	1984-85	Rapeseed	Dark Brown	Bradwell	L	90	Norstar		Irrigation
33. Clair	1984-85	Rapeseed	Black	Yorkton	CL	42	Norstar		Good
34. Strasbourg	1984-85	Flax	Dark Brown	Weyburn	L	58	Norstar		Poor
35. Carlyle	1985-86	Mustard	Dark Brown	Weyburn	L	73	Norstar		Good
36. Paddockwood	1985-86	Rapeseed	Dark Gray	Pelly	L	46	Norstar		Poor
37. Porcupine Plain	1985-86	Summerfallow	Gray Luvisol	Etomami	CL	311	Norstar		Average
38. Handel	1985-86	Spring wheat	Dark Brown	Elstow	L	100	Norstar		Average
39. Clair	1985-86	Barley	Black	Yorkton	L	47	Norstar		Average
40. Indian Head	1985-86	Barley	Black	Indian Head	HC	44	Norstar		Average

† Rapeseed (Brassica campestris L.), Barley (Hordeum vulgare L.), winter and spring wheat (Triticum aestvum L.), Flax (Linum usitatissimum L.), Mustard (Sinapsis alba L.).

‡ According to the Canadian System of Soil Classificaiton, 1978. The Canadian Soil Classification terms Black Chernozemic, Dark brown Chernozemic, Brown Chernozemic, Dark Gray Chernozemic and Gray Luvisol infer the United States Soil Classificaiton terms of Udic Boroll, Typic Boroll, Aridic Haploboroll, Boralfic Boroll, Boralf, respectively. L-Loam, Si-Silty, C-Clay, H-Heavy, F-Fine, S-Sandy.

§ NO_3-N determined for the surface 60 cm when sampled in the early spring of each crop year.

¶ Irrigation - Approximately 65 cm total growing season moisture
Good - Above average rainfall which was well distributed during the growing season. Moisture reserves adequate to cope with wind and heat stress experienced.
Average - No extended dry periods. Heat and/or wind stress may have been yield reducing factors
Poor - Periodic drought combined with heat and/or wind stress.

\# Three test sites in the Clair area, one of which caught a heavy thunderstorm in early July.

Table 2. Relative agronomic performance of winter wheat and rye cultivars utilized in these studies. Average of 10 station years for the region where the N fertilizer trials were conducted.

	Heading (da)	Maturity (da)	Height (cm)	Hectoliter wt. (kg)	Kernel wt. (mg)	Yield
a)	Deviation from Puma					% Puma
Puma	0	0	0	0	0	100
Cougar	+1	0	-9	0	-1	90
Frontier	-1	-1	+3	+2	0	84
b)	Deviation from Norstar					% Norstar
Norstar †	0	0	0	0	0	100
Sundance	0	-1	-1	0	+1	100

†The main advantages of Norstar over Sundance are improved quality and winter hardiness.

Table 3. Average heading date, maturity and height of winter wheat and rye. See Table 1 for locations.

	Heading Date (da/mon)		Date Ripe (da/mon)		Height (cm)	
Location	Wheat	Rye	Wheat	Rye	Wheat	Rye
1	6/7*	20/6*	8/8**	4/8**	114*(-)	135*(-)
2	27/6	5/6	5/8	31/7	86**(+)	92**(+)
3	20/6	1/6	28/7**	23/7**	86**(+)	94
4	21/6	1/6	1/8	25/7	87**(+)	104**(+)
5	21/6	1/6	31/7	26/7**	82**(+)	90**(-)
6			29/7	20/7	79	101
7			1/8	19/7	75	92
8	28/6	10/6	5/8	1/8	85**(+)	101**(+)
9	26/6	10/6	6/8	2/8	88**(+)	96**(-)

*,** Differences due to increased N fertilizer rates at the significant 5 and 1% probability levels as tested by a F test. Increased nitrogen fertilizer rates delayed heading and maturity and increased (+) or decreased (-) height in trials where significant differences were detected.

site were corrected to include N applied as mono-ammonium phosphate.

Soil samples were collected at each site in the late fall and early spring for nutrient analyses. Available N levels estimated for the surface 60 cm of soil samples collected in the early spring were utilized in this study (Table 1), as these were considered the best estimates of soil available N (Malhi et al. 1985). Soil and fertilizer N were considered to be equally plant-available, and therefore, total available N was calculated as the sum of available soil N to 60 cm depth, as estimated from the soil test, plus added fertilizer N (Heapy et al. 1976, Zentner and Read 1977, France and Thornley 1984, Bole and Dubetz 1986). Fertilizer N was added as early spring broadcast ammonium nitrate (34-0-0) at 0, 34, 67 and 101 kg ha^{-1} at all sites; additional rates of 135, 202 and 303 kg ha^{-1} were also used at some sites.

Soil was moist to a depth of at least 60 cm in the spring at all sites. General environmental conditions were monitored throughout the growing season (Table 1).

Heading date, maturity, height, seed size, grain test weight and yield (8% H_2O) were measured at the appropriate stages. Protein percentages were determined as Kjeldahl N (Nx5.7) or by the Udy dye method (1971), and results are reported on a 14.0% moisture basis. Kjeldahl analyses were utilized to standardize protein concentrations in each trial analyzed by the Udy dye method. Protein percentages were determined by the Kjeldahl method for all trials that included both wheat and rye.

Analyses of variance were conducted to determine the significance of treatment differences within each fertilizer trial. Polynomial, Mitscherlich, logistic and Gompertz equations were considered to describe the relationship between protein concentration and total plant available

N. The following form of the Gompertz equation provided the most complete description of this relationship:

$$Y = C + Ae^{-Be^{-KN}} \qquad (1)$$

where Y = predicted protein concentration (%)

C = minimum protein concentration (%)

A = asymptotic protein concentration achieved at high N levels

B = coefficient that influences point where protein concentration becomes greater than C.

K = coefficient that determines the rate Y increases to A.

N = total available N.

The fertilizer-N response equation (Eq. 2) outlined by France and Thornley (1984) was used to analyze the relationship of winter wheat and rye total grain and grain protein yields to total available N.

This function takes the form:

$$Y = \frac{(1.0 - N/DEP) \times MAX \times N}{N + MAX/SLOPE} \qquad (2)$$

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

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

DEP = regression coefficient, a constant which accounts for yield depression at high N levels.

MAX = asymptotic yield which could be achieved with high levels of N if no yield depression were to occur.

SLOPE = regression coefficient, the slope of the fertilizer response equation for the first incremental increase in N; fertilizer use efficiency for grain and grain protein production. The maximum grain and grain protein yields of the predicted response curves (Y_{MAX}), and the level of total available N at which maximum yield is obtained (N_{MAX}) were calculated using equations 3 and 4 from France and Thornley (1984).

$$Y_{MAX} = MAX\left(1 - \frac{2\ MAX}{SLOPE \times DEP}\left[\left(1 + DEP\ \frac{SLOPE}{MAX}\right)^{\frac{1}{2}} - 1\right]\right) \qquad (3)$$

$$N_{MAX} = \frac{MAX}{SLOPE}\left[\left(1 + DEP\ \frac{SLOPE}{MAX}\right)^{\frac{1}{2}} - 1\right] \qquad \begin{matrix} P_{MAX} \rightarrow \infty \\ K_{MAX} \rightarrow \infty \end{matrix} \qquad (4)$$

RESULTS AND DISCUSSION

Winter wheat was significantly ($P \leq .01$) later heading, later maturing and shorter than winter rye in all trials where comparisons could be made (Table 3). Winter wheat also had significantly ($P \leq .01$) larger seed size and higher hectoliter weight than rye (Table 4). Winter rye significantly ($P \leq .05$) outyielded winter wheat in 15 out of 19 trials. Yield differences between the two species were not significantly ($P > .05$) different in the remaining four trials. The grain protein concentration of winter wheat was significantly ($P \leq .05$) higher than winter rye in all comparable trials except for locations 2, 6 and 10. However, protein concentration did not prove to be a good indicator of protein productivity. Higher grain yields for rye compensated for lower grain protein concentrations with the result that, at equal N rates, rye produced as much, or more, protein ha^{-1} than wheat in all trials except for location 2. The superior protein producing ability of rye was demonstrated in 58 percent of the trials where rye produced significantly ($P \leq .05$) more protein ha^{-1} than wheat.

Nitrogen (N) fertilizer did not have a significant ($P > .05$) influence on heading date, maturity (Table 3), hectoliter weight or kernel size (Table 4) in most trials. Where a significant ($P \leq .05$) N response was

Table 4. Average hectoliter and 1000 kernel weight of winter wheat and rye. See Table 1 for locations.

	Hectoliter Weight (kg)		Kernel Weight (mg)	
Location	Wheat	Rye	Wheat	Rye
1	81.6*	74.3**	33.9**	24.1**
2	79.3	74.9	30.0**	22.4**
3	81.8	76.8*	31.7	23.4**
4	82.7	77.9*	37.4	27.4
5	81.9**	77.8**	34.1**	24.4**
6	82.5	74.0	36.0	18.1
7	81.7	72.9	33.3	16.4
8	77.1	74.8	31.1	25.6
9	78.8	74.0	33.9	25.9
10	77.5	72.0	32.3*	29.2*
11	76.4**	70.3**	29.8	19.4**
12	N/A	N/A	N/A	N/A
13	75.9	71.0	25.6	22.4*
14	76.7*	70.4*	28.7**	22.4**
15	79.1	71.0	38.6	34.0
16	79.8	73.4	36.5	34.0
17	78.3		25.4	
18	80.3		32.7	
19	78.5		28.7	
20	81.0	73.2	37.8	29.1
21	80.0*	71.1	32.2	28.5
22	80.0	72.6	34.2	29.0
23	78.8	71.5	31.5	28.8
24	79.1		35.4**	
25	79.0		32.9*	
26	80.2		31.1	
27	77.8		32.6**	
28	76.9		25.4	
29	76.2		25.8	
30	74.4**		22.6**	
31	78.4**		26.4**	
32	80.2		36.9	
33	77.5		36.5	
34	75.9		26.8	
35	79.3*		33.7	
36	79.4		31.6	
37	78.8		33.1	
38	74.3		25.0	
39	78.6		31.4	
40	N/A		34.7	

*,** Decreases due to increased N fertilizer rates significant at the 5 and 1 percent probability levels as tested by a F test.

detected, maximum differences were a one and two day delay in heading, a two and nine day delay in maturity, a three and three kg reduction in hectoliter weight, and a seven and nine mg reduction in seed size for wheat and rye respectively. A significant ($P \leq .05$) N response was observed more frequently for height (Table 3). In this instance the response was not directional and increases up to 25 and eight cm and reductions to nine and nine cm were observed with increased N for wheat and rye, respectively.

The addition of N fertilizer resulted in significant ($P \leq .05$) grain yield increases for winter wheat and rye in all trials except 6, 7, 11, 29 and 37. The residual soil N was exceptionally high and/or a severe late season drought was experienced at these five locations (Table 1). Increased levels of N fertilizer caused significant ($P \leq .05$) grain yield reductions for locations 6 and 11.

Nitrogen fertilization had a significant ($P \leq .05$) influence on protein concentration in 78 percent of the winter wheat (Table 6) and 90 percent of winter rye trials (Table 7). Added N had a significant ($P \leq .05$) influence on protein yield in all trials except locations 7,11,29 and 37. As previously noted these four locations had high residual soil N and/or experienced a severe late season drought that also limited grain yield responses to added N.

The above observations indicate that increased levels of N have a greater measureable effect on height, grain yield, protein concentration and protein yield than on heading date, maturity, hectoliter weight and seed size. It was also evident that response to increased N levels was not always the same for winter wheat and rye. Dissimilar height responses were indicated by a significant ($P \leq .05$) species by N fertilizer rate

Table 5. Estimated regression coefficient (MAX), maximum predicted yield (Y_{MAX}) and yield-maximizing N levels (N_{MAX}) for winter wheat and winter rye, 1974-86. MAX from equation 2, Y_{MAX} determined from equation 3 and N_{MAX} determined from equation 4 Materials and Methods.

	WINTER WHEAT				WINTER RYE			
LOCATION	MAX	Standard error	Y_{MAX} (kg grain yield ha^{-1})	N_{MAX} (kg N ha^{-1})	MAX	Standard error	Y_{MAX} (kg grain yield ha^{-1})	N_{MAX} (kg N ha^{-1})
1	5313	222	2947	201	8152	235	4191	194
2	5603	193	3060	205	5225	460	3057	166
3	6437	726	3371	215	6539	475	3596	180
4	8454	535	4044	236	9837	816	4750	207
5	6771	235	3490	219	8132	497	4184	194
6	5545	348	3038	204	4144	347	2568	152
7	3799	176	2303	178	3538	449	2272	143
8	6254	1039	3304	213	9854	536	4755	207
9	7797	379	3835	229	8484	440	4306	197
10	4820	153	2747	194	5387	309	3126	168
11	1588	293	1147	125	2686	305	1825	128
12	2952	147	1897	161	4323	255	2652	155
13	3198	262	2019	166	3774	320	2390	147
14	3145	173	1993	165	3339	108	2171	140
15	9621	512	4391	246	N/A	N/A	N/A	N/A
16	6167	1142	3273	212	7640	2009	4010	190
17	2663	579	1749	155				
18	2874	81	1858	160				
19	3596	218	2210	174				
20	958	106	743	101	2442	89	1689	123
21	5716	176	3103	206	9008	1047	4482	201
22	4421	478	2579	188	10918	1956	5079	214
23	6579	399	3422	217	7710	626	4035	191
24	12561	521	5159	266				
25	10288	1610	4578	251				
26	7747	1043	3819	229				
27	9903	489	4471	248				
28	2437	50	1630	150				
29	1866	37	1312	134				
30	1568	43	1135	125				
31	4937	604	2795	196				
32	26600	3649	7589	323				
33	10162	811	4543	250				
34	2195	148	1498	143				
35	8541	235	4070	236				
36	4253	279	2506	185				
37	10308	697	4583	251				
38	2912	208	1877	161				
39	5852	424	3155	208				
40	6018	559	3218	210				

Table 6. Estimated regression coefficients for protein concentration and estimated protein yield regression coefficient (MAX), maximum predicted grain protein yield (Y_{MAX}) and protein yield-maximizing N levels (N_{MAX}) for winter wheat.

Location	Protein Concentration† Regression Coefficient A	Protein Concentration† Regression Coefficient B	Regression Coefficient‡ MAX	Regression Coefficient‡ Std. Error	N_{MAX}‡ (kg N ha^{-1})	Y_{MAX}‡ (kg protein yield ha^{-1})
1	5.92	13.83	1123	50	290	436
2	4.59	19.23	945	64	276	394
3	3.65	6.87	1100	148	289	431
4	2.85	31.67	1259	120	300	464
5	3.83	11.60	1182	57	295	448
6	6.08	71.71	1079	65	287	426
7	5.90	56.16	667	39	248	318
8	4.77	23.44	1073	158	287	425
9	5.18	11.19	1813	147	329	557
10	4.26	7.53	887	39	271	280
11	11.39	3.03	379	76	204	216
12	7.27	4.78	621	21	243	304
13	5.65	1.01	804	212	263	358
14	7.99	7.02	706	67	253	330
15††	4.26	0.24	3440	1134	375	724
16	8.97	41.57	1024	311	283	413
17††	1.94	33.33	281	66	183	173
18	3.40	1.28	479	14	222	255
19††	9.90	86.21	374	22	203	214
20	5.88	0.49	170	29	150	116
21	2.75	13.62	853	34	268	371
22	8.64	26.31	656	657	247	315
23	3.71	4.14	1526	214	315	513
24	3.87	10.18	4161	730	387	771
25	2.12	15.64	1550	329	316	517
26††	9.40	60.47	882	173	271	379
27	3.40	32.27	1585	71	318	523
28	5.16	2.89	421	16	212	233
29	4.01	5.62	267	12	179	166
30	5.14	6.20	212	16	164	139
31	3.85	10.55	736	102	256	339
32††	4.01	0.52	3209#		213	887
33	3.28	6.97	2790	697	360	671
34	4.73	1.04	390	46	207	220
35	4.33	20.11	1896	236	332	569
36††	3.44	6.76	674	68	249	320
37††	3.25	11.90	1704	156	324	541
38††	2.66	14.01	375	26	204	214
39	5.91	11.18	1411	158	309	492
40††	3.10	0.10	1277	372	301	467

† Equation 1 Materials and Methods. C = 8.5 and K = 0.02302.

‡ MAX from equation 2, N_{MAX} determined from equation 4 and Y_{MAX} determined from equation 3 Materials and Methods.

†† Protein concentrations of 12.7, 8.6, 8.5, 8.0, 12.5, 10.8, 11.7, 10.5 and 11.6 were observed for locations 15,17,19,26,32,36,37,38 and 40, respectively. Increased rates of N did not produce a significant ($P \leq .05$) change in protein concentration for the N rates considered in these trials.

For this location, least-square analyses did not produce a value for MAX when DEP = 948.8 and SLOPE = 4.9. Least-squares analysis was successful when all 3 regression coefficients were estimated for this location; SLOPE = 11.5, DEP = 587.3 and MAX = 3209.

ble 7. Estimated regression coeficients for protein concentration and estimated protein yield regression coefficient (MAX), maximum predicted grain protein yield (Y_{MAX}) and protein yield-maximizing N levels (N_{MAX}) for winter rye.

cation	Protein Concentration† Regression Coefficient A	B	Regression Coefficient‡ MAX	Std. Error	N_{MAX}‡ (kg N ha^{-1})	Y_{MAX}‡ (kg protein yield ha^{-1})
1	4.30	32.02	1571	91	291	517
2	3.03	16.59	781	100	240	350
3	3.34	11.15	1048	133	262	417
4	2.97	38.59	1683	307	296	535
5	3.55	19.50	1433	118	285	494
6	6.62	50.23	761	68	238	345
7	7.26	39.14	676	84	229	320
8	4.27	51.89	1898	418	305	566
9	3.34	9.93	1598	46	292	522
10	5.92	6.27	1311	61	278	472
11	6.28	2.06	538	127	212	275
12	6.74	8.16	956	82	255	395
13	7.03	4.65	863	173	247	372
14	6.65	8.00	666	62	228	317
15††	4.40	0.52	- - - - HAIL DAMAGE - - - -			
16	1.19	39.76	855	409	246	370
20	4.76	3.09	405	16	192	226
21††	4.50	0.17	2696	369	328	658
22	2.85	52.96	1793	430	301	552
23	6.44	17.70	2461	701	322	634

†Equation 1 Materials and Methods. C = 8.0 and K = 0.02302.

‡ MAX from equation 2, N_{MAX} determined from Equation 4 and Y_{MAX} determined from Equation 3 Materials and Methods.

††Protein concentrations of 12.3 and 12.4% were observed for locations 15 and 21 respectively. Increased rates of N did not produce a significant ($P \leq .05$) change in protein concentration for the N rates considered in these trials.

interaction for this character in 67 percent of the trials where comparisons could be made. Responses to N by wheat and rye were more similar for the remaining characters. The species by N fertilizer rate interaction was significant ($P \leq .05$) for heading date, maturity, seed size, hectoliter weight and yield in 0,33,25,15 and 10 percent of the trials, respectively. The species by N fertilizer rate interaction was significant ($P \leq .05$) for protein concentration and protein yield in 37 percent of the trials.

The potential for grain yield increase through the use of inorganic N fertilizer has been recognized for over a century. However, describing this response mathematically still presents a methodological challenge. Part of the difficulty in describing N response lies in the fact that fertilizer is not the only source of N available to the plant. Consequently, data from individual fertilizer trials reveal only part of the grain yield N response curve. In addition, because residual soil N varies from trial to trial, it is difficult to compare response curves from different trials unless variations in soil N supply are taken into account. Unfortunately, plant available soil N cannot be determined with precision. Soil N exists in several interacting pools that have different plant availability. The movement of N among these pools, e.g., mineralization, fixation, immobilization, etc., is influenced by environmental factors, e.g., temperature, moisture, crop residue, etc., with the result that plant available N constantly changes throughout the cropping season. Fertilizer N also enters into these complex interactions making it extremely difficult to obtain a precise measure of total plant available N. Given these limitations, available soil N, as estimated from soil tests, and fertilizer N were considered to be equally plant-available in this study (Heapy et al. 1976, Zentner and Reed 1977, France and Thornley 1984, Bole and Dubetz 1986). Total available N was calculated as the sum of available soil N plus added fertilizer N thereby allowing for the relative positioning of fertilizer N response curves for different trials.

The Mitscherlich equation has been frequently employed to describe yield responses to fertilization (Engelstad and Khasawnch 1969). Unfortunately, the Mitscherlich equation did not accommodate the yield depression found at high N levels in high stress environments in this study. Yield depression at high N levels has been frequently observed (Terman et al. 1969, Stanford and Hunter 1973, Mengel and Kirkby 1979, Caliandio et al. 1981) and becomes an important consideration in N management under the marginal moisture conditions experienced with extended rotations in semi-arid climates like that of the western Canadian prairies. Many researchers have shown a preference for polynomial equations to describe grain yield responses to N fertilizer (Mason 1956). These equations are simple to fit; however, because different fertilizer trials often sample different regions of the N response curve, the resulting equations usually take on a variety of forms. In addition, nonlinear responses in which a variable appears in a equation more than once, e.g., quadratic equations, are often difficult to interpret biologically. The inverse polynomial function outlined by France and Thornley (1984) provides another option that has been employed to describe fertilizer response. This type of equation (Equation 2) was chosen in the present study because it provided a curvilinear yield - N fertilizer response surface that conformed well with the general grain yield trends observed in the field data.

Grain yield data from fourteen winter wheat and nine winter rye fertilizer trials provided samples of the N response curve that were complete enough to allow for least square estimates of the three regression coefficients SLOPE, MAX and DEP in equation 2. Within species, SLOPE of the grain yield response curves were similar for these trials (mean SLOPE = 65.8 for wheat and 88.5 for rye). Values of the coefficient accounting for grain yield depression at high N levels (DEP) were also similar (mean DEP = 903 for wheat and 800 for rye). In the remaining trials, limitations imposed by the regions of the response curve sampled prevented least squares estimates of the regression coefficients in equation 2. Consequently, the mean values for SLOPE and DEP determined above were utilized to obtain least square estimates of the coefficient MAX (Table 5) and grain yield response equations (Figure 1 and 2) for all winter wheat and rye N fertilizer trials. Predicted grain yields from these equations explained 96 and 88 percent of the variability in actual yield for wheat and rye, respectively, indicating that they provided excellent expressions of grain yield response to N fertilization (Figure 3 and 4).

The SLOPE value in equation 2 may be considered a measure of initial N fertilizer use efficiency in grain production. This value may be influenced by both plant and soil characteristics. In this study, values for SLOPE indicate that the initial N fertilizer use efficiency in wheat grain production was only 89 percent of rye. Factors such as differences among genotypes in root feeding depth, thereby allowing plants different access to N, and/or differences in internal N use efficiency would be expected to produce differences in SLOPE. Although not factors in species comparisons in this study, variables such as N volatization,

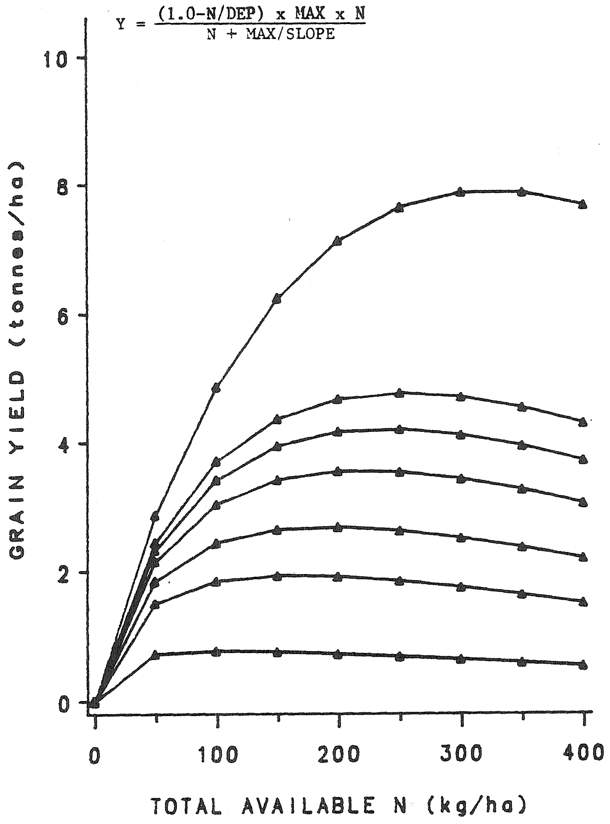

Figure 1. Relationship between grain yield and total available nitrogen for winter wheat.

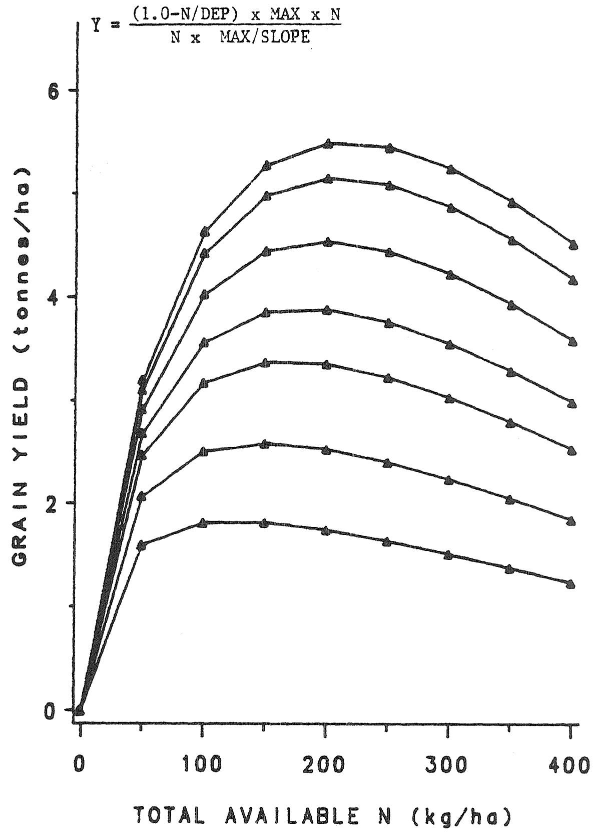

Figure 2. Relationship between grain yield and total available nitro for winter rye.

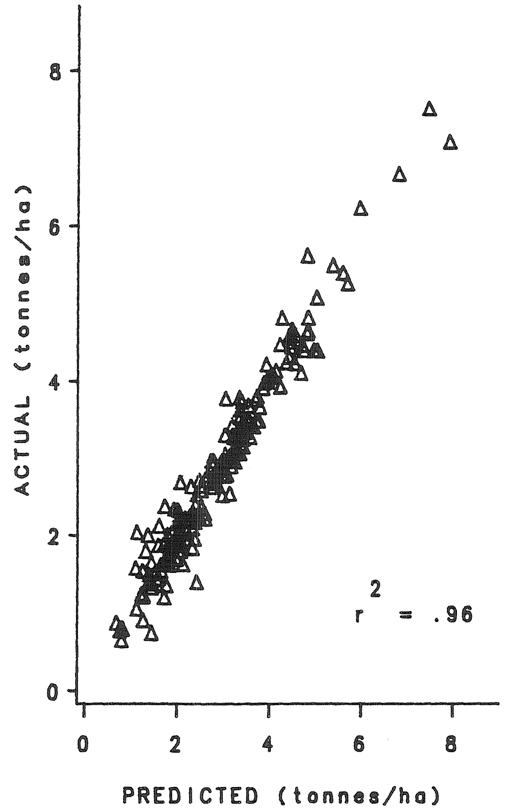

Figure 3. Predicted versus actual winter wheat grain yields.

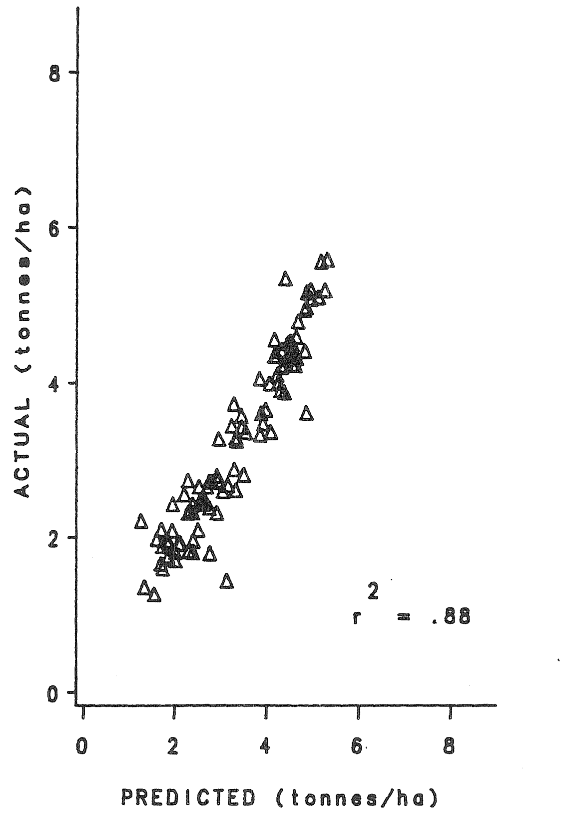

Figure 4. Predicted versus actual winter rye grain yields.

immobilization, etc., of added N fertilizer would also be expected to influence SLOPE values.

Grain yield depression from excessive N supply is often associated with luxuriant growth that results in lodging and/or increased incidence of diseases. Neither of these factors presented problems in the present study. Even at high rates of N fertilization under irrigation conditions there was no apparent lodging or increased incidence of diseases. Consequently, it appears that the grain yield depression (DEP) observed in this study was more of a physiological response to high N levels.

Grain yield increases from added N were not due to increases in the yield component seed size (Table 4). Therefore, maximum sink size was determined at or before the completion of spikelet initiation. Apparently the only adjustments to N supply to take place after this stage of development were compensation for adverse environmental conditions through tiller loss, floret abortion (blasting) and/or, as a last resort, reduced seed size.

The asymptotic maximum, or grain yield potential MAX in equation 2 accounted for most of the variability in grain yield response to N fertilizer among the trials in this study (Table 5). Within species, SLOPE and DEP were held constant in equation 2. Therefore, differences in maximum predicted grain yield (Y_{MAX}) and level of total available N at which maximum grain yield was obtained (N_{MAX}) were determined by differences in MAX (Figure 1 and 2). MAX may be influenced by both environment (Table 1) and genotype (Table 2).

The large influence of environment in determining grain yield N response was demonstrated by three- and ten-fold increases in Y_{MAX} due to locations for Puma rye and Norstar wheat, respectively (Table 5). The difficulties in predicting N requirements for maximum grain yield in this region of the American Great Plains were emphasized by the fact that these environmentally dependent increases required 1.7- and 3.2-fold increases in N (N_{MAX}) for rye and wheat, respectively. A large number of environmental factors have been shown to influence grain yield response to N fertilizer. However, on the Great Plains of North America, moisture supply is considered to be the chief factor limiting N response (Terman et al. 1969, Smika and Greb 1973). In the present study, the N responses obtained under irrigation compared to conditions of extreme drought clearly demonstrate the interdependence of N and water in determining grain yield (Table 1 and 5). In addition, the importance of moisture distribution over the growing season should not be underemphasized. Without exception, the lowest yielding trials in this study were victims of mid- or late-season droughts that would not have been predicted on the basis of spring moisture reserves.

The importance of genotypic differences in determining grain yield response to N fertilizer were also demonstrated in this study. In comparative trials, Y_{MAX} for rye averaged 25 percent more and required 10 percent less N fertilizer (N_{MAX}) than wheat (Table 5). Consequently, in addition to a greater N use efficiency, the winter rye cultivars utilized had a greater grain yield potential than the winter wheat cultivars when produced in these environments.

Considerable difficulty was experienced in describing grain yield responses to added N fertilizer. Lack of precision in estimates of residual plant-available soil N, the influence of environment in modifying the N cycle, and the fact that N fertilizer trials usually sample only part of the N response curve made it difficult to compare results from different trials. These factors also restrict our ability to obtain a clear picture of the complete N response curves for grain protein concentration and grain protein yield.

The N response curves for protein concentration were similar for winter wheat and rye. After an initial lag (lag phase), protein concentration increased rapidly (increase phase), and then tailed off at high N levels (Fig. 5 and 6). The length of the initial lag phase of the curve was reflected by the size of the B value in equation 1 (Table 6 and 7). For several locations, the lag phase extended beyond the 50 kg ha^{-1} N level (Fig. 5 and 6) with the suggestion that there may be an initial decrease in protein concentration (Bole and Dubetz 1986, Partridge and Shaykewich 1972). The presence of an initial lag phase in the protein concentration N response curve suggests that a minimum grain protein concentration exists for each species. The mean protein concentration for locations with no increase for at least the first two N levels sampled indicated that the minimum grain protein concentration was approximately 8.5 and 8.0 percent for wheat and rye, respectively. These values were employed as estimates of C in equation 1. The increase phase of the grain protein concentration N response curve was similar for both wheat and rye. Therefore, the coefficient K, that determines the rate at which grain protein concentration increases to its asymptote, was also held constant in equation 1 (Table 6 and 7). The asymptotic protein concentration achieved at high N levels (C+A in equation 1) varied among locations. Consequently, the two coefficients A and B in equation 1 were determined by least square estimates, with C and K held constant as indicated above, to give grain protein concentration N response equations for each wheat (Table 6) and rye (Table 7) fertilizer trial. Predicted grain protein concentration from these equations explained 98 and 93

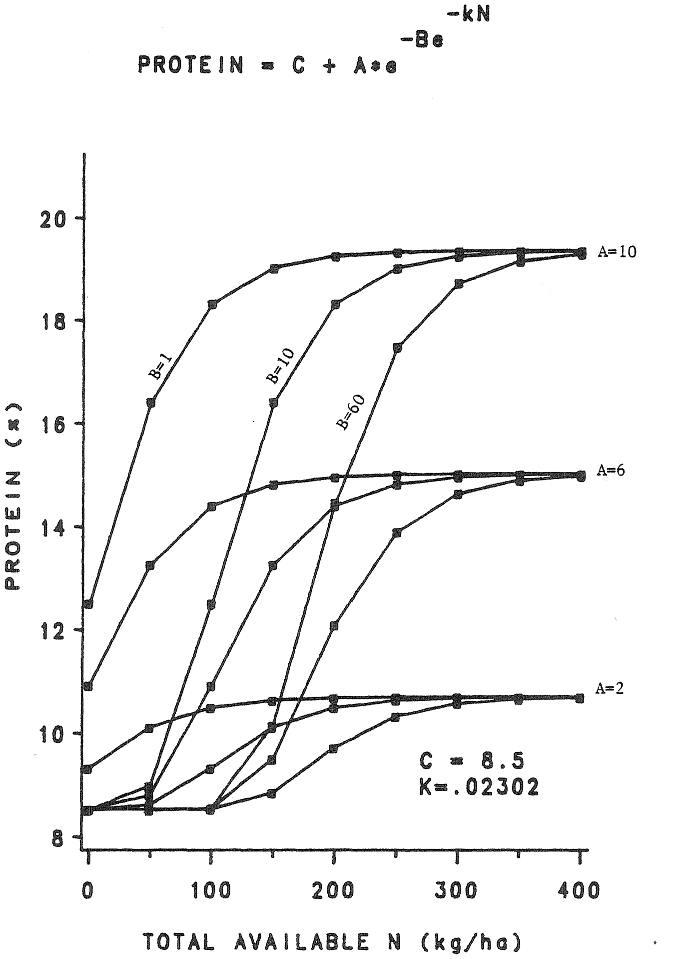

Figure 5. Relationship between protein concentration and total available nitrogen for winter wheat.

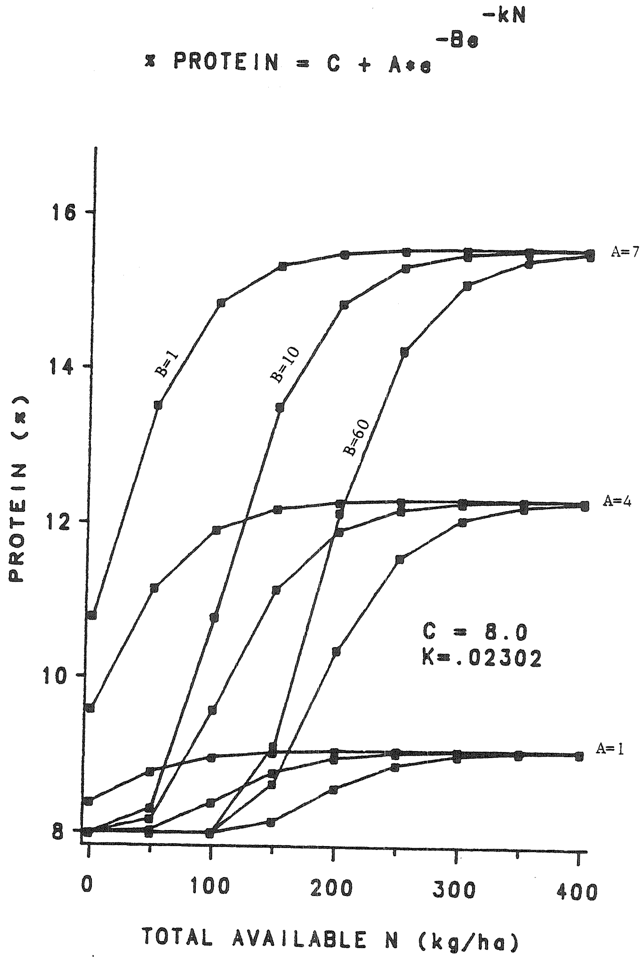

Figure 6. Relationship between protein concentration and total available nitrogen for winter rye.

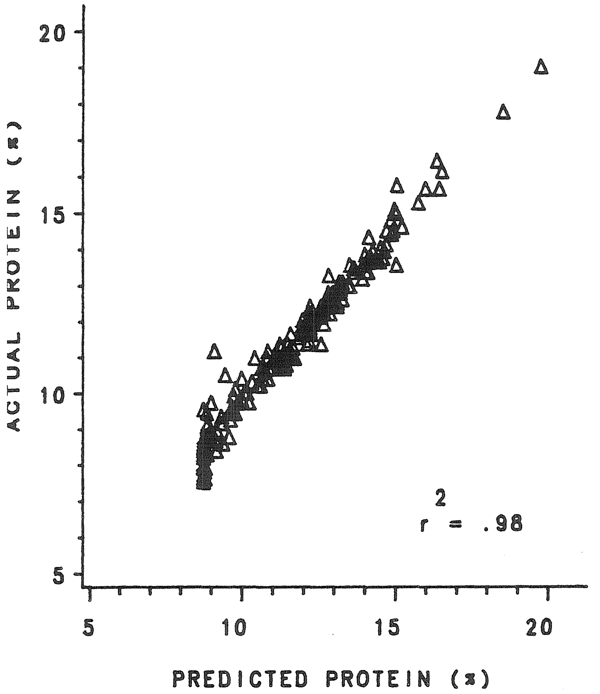

Figure 7. Predicted versus actual protein concentration for winter wheat.

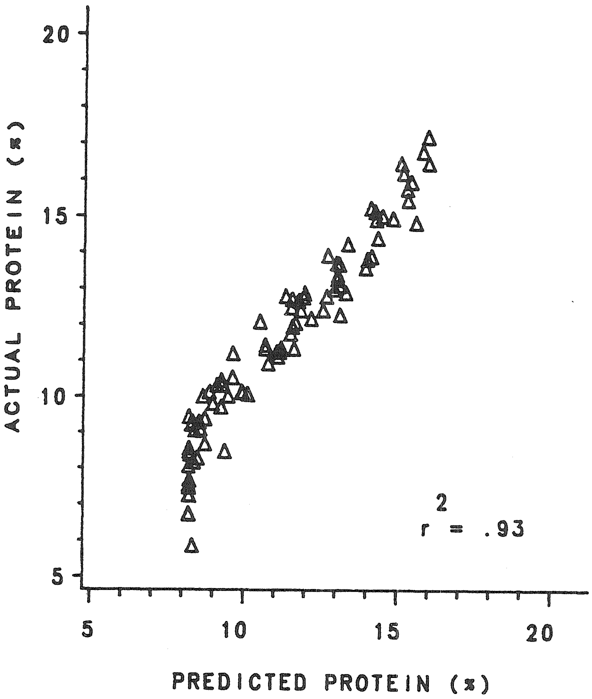

Figure 8. Predicted versus actual protein concentration for winter rye.

percent of the variability in actual grain protein concentrations for wheat (Fig. 7) and rye (Fig. 8), respectively.

The above observations suggest a strong genotypic influence on minimum grain protein concentration (C) and the rate (K) at which protein concentration increases to its asymptote. In contrast, large location effects indicate that the relative length of the initial lag phase (B) and the asymptotic protein concentration achieved at high N levels (A) are both under greater environmental influence. Yield is considered to be a good measure of the cumulative influence of environment upon plant growth, i.e., the more favorable the environment the greater the yield. However, neither the asymptotic protein concentration (A) nor the relative length of the lag phase (B) were significantly (P>.05) correlated with maximum grain protein yield (Y_{MAX}) indicating that the response to environmental cues determining protein concentration differ from those for yield in these trials. These differences should not be completely unexpected because the periods of maximum nitrogen assimilation (prior to anthesis) and grain carbohydrate synthesis (after anthesis) are subject to different environmental emphasis during early and late plant growth stages. This change in emphasis would be expected to have a major influence on final protein concentration which is determined by the relative relationship between grain protein yield and total grain yield.

The inverse polynomial function outlined by France and Thornley (1984) provided a useful description of total grain yield response to N for these trials. The N response curve for grain protein yield took a form similar to that observed for total grain yield (Fig. 1 and 2). Consequently, the inverse polynomial function also provided a curvilinear yield - N fertilizer response surface that conformed well with the grain protein yield data for these trials. Protein yield data from seven winter wheat and four winter rye fertilizer trials provided samples of the N response curve that were complete enough to allow for least squares estimates of the three regression coefficients SLOPE, MAX and DEP in equation 2. With one exception (Table 6), SLOPE of the protein yield response curves were similar within species (mean SLOPE = 4.9 and 5.3 for wheat and rye, respectively). Values of the coefficient accounting for protein yield depression at high N levels (DEP) were also similar (mean DEP = 949 and 869 for wheat and rye, respectively). These mean values of SLOPE and DEP were utilized as constants to obtain least square estimates of the coefficient MAX, and complete protein yield response equations, for each winter wheat (Table 6, Figure 9) and rye (Table 7, Figure 10) N fertilizer trial. Predicted protein yields from these equations explained 94 and 89 percent of the variability in actual protein yield for wheat and rye, respectively (Figure 11 and 12).

The SLOPE value in equation 2 may be considered a measure of initial N fertilizer use efficiency in grain protein production. In this study, the values for SLOPE suggest that, under low available soil N levels, 86 (4.9/5.7 x 100) and 92 (5.3/5.7 x 100) percent of the initial increment of N fertilizer was recovered as grain N for wheat and rye, respectively. However, the approximate nature of these estimates is emphasized when one considers that the initial N recovery for wheat at location 32 was 202 (11.5/5.7 x 100) percent (Table 6). In this instance, it is probable that the residual soil N available to the plant was severely underestimated. The mean values for SLOPE indicate that the initial N fertilizer use efficiency in wheat grain protein production was only 92 percent of rye. As expected, this value is similar to the relative initial N use

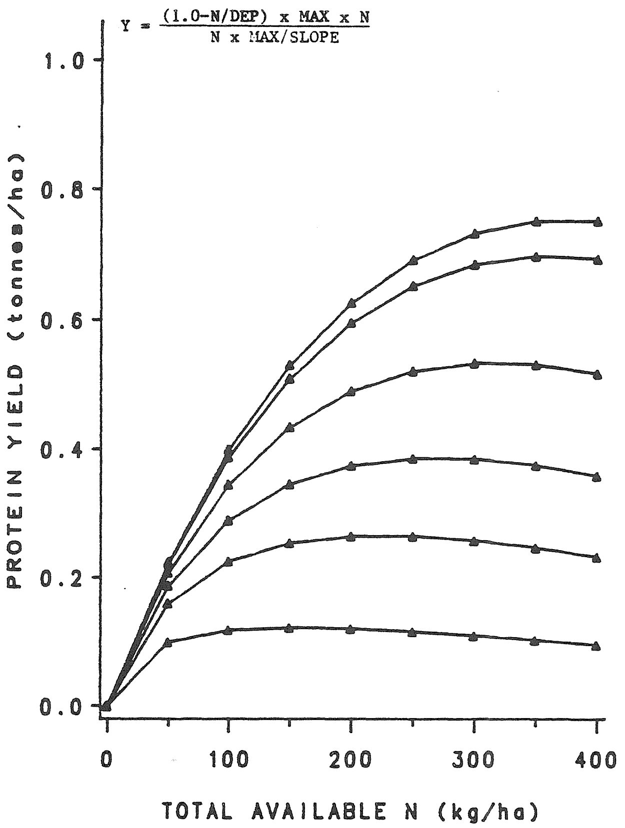

Figure 9. Relationship between protein yield and total available nitrogen for winter wheat.

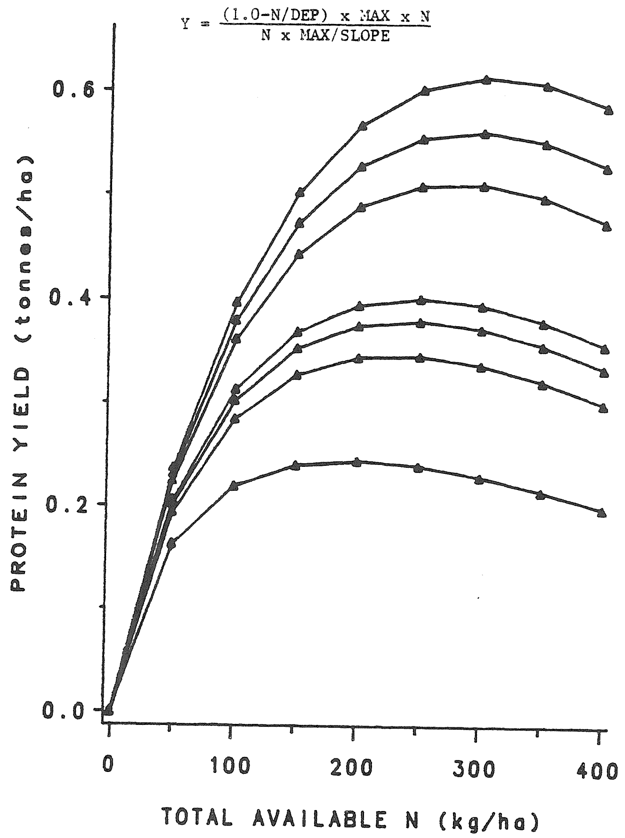

Figure 10. Relationship between protein yield and total available nitrogen for winter rye.

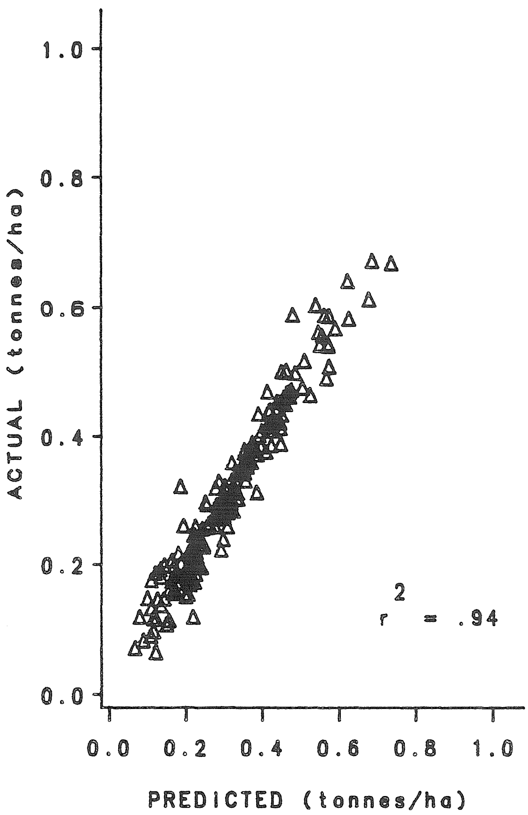

Figure 11. Predicted versus actual winter wheat grain protein yields.

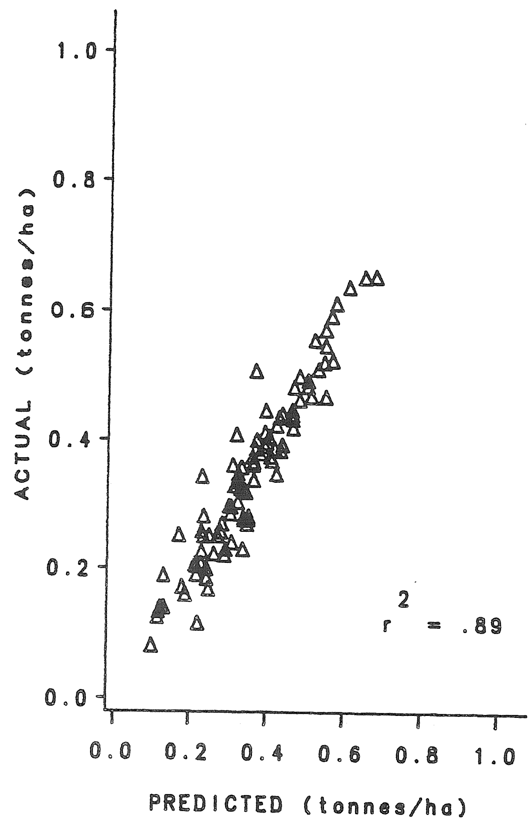

Figure 12. Predicted versus actual winter rye grain protein yields.

efficiency of 89 percent for total grain production of wheat compared to rye.

Grain yield depression was observed at high N levels in the present study. Increases in grain protein concentration at high N levels did not compensate for reductions in grain yield with the result that decreases in grain protein yield were also evident at high N levels. The absence of increased lodging and level of diseases with increased N rates suggests that the protein yield depression (DEP) was also a physiological response to high N levels.

The asymptotic maximum, or protein yield potential MAX in equation 2, accounted for most of the variability in grain protein yield response to N fertilizer among the trials in this study (Tables 6 and 7). Within species, SLOPE and DEP were held constant in equation 2. Consequently, differences in maximum predicted grain protein yield (Y_{MAX}) and level of total available N at which maximum protein yield was obtained (N_{MAX}) were determined by differences in MAX (Fig. 9 and 10). A poor relationship (r = .18 and -.25 for wheat and rye, respectively) existed between maximum protein concentration(C+A)and maximum protein yield (Y_{MAX} in Tables 6 and 7). In contrast, maximum protein yield(Tables 6 and 7)was highly dependent (r = .93** and .84** for wheat and rye respectively) upon maximum total predicted grain yield (Table 5). As a corollory to these observations, differences in total grain yield are a better indicator of difference in protein productivity than are differences in grain protein concentration.

Total grain yield N response has been shown to be highly dependent upon environmental variables. A similar large environmental dependency was observed for grain protein yield responses to N in these trials. For example, location effects accounted for 2.9 and 7.6-fold increases in

Y_{MAX} of Puma rye (Table 7) and Norstar wheat (Table 6), respectively. The difficulty in predicting N requirements in this region was once again emphasized by the fact that 1.7 and 2.6-fold increases in N were required to achieve these environmentally dependent increases in Y_{MAX} for wheat and rye grain protein yield, respectively. The large grain protein yield N response obtained under irrigation compared to conditions of extreme drought in these trials also emphasizes a strong interdependence of N and water in determining grain protein yield (Table 6).

A confounding of genotypic differences with location effects prevented a comparison of cultivars within species for this study. Between species, it has been demonstrated that rye requires 10 percent less N fertilizer to produce 25 percent greater maximum predicted total yield than wheat. The lower grain production by wheat is accompanied by a higher maximum grain protein concentration, i.e., mean values of 14.2 percent for wheat (Table 6) versus 12.8 percent for rye (Table 7) in comparable trials. However, mean maximum grain protein yield for wheat was only 87 percent of rye even though plant-available N levels for maximum grain yield were estimated to be approximately the same (mean values of 268 kg ha^{-1} for wheat and 266 kg ha^{-1} for rye). These observations lend further support to the contention that winter rye has a greater N use efficiency than winter wheat.

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