THE EFFECT OF GRANULAR FERTILIZER N-FORM, PLACEMENT AND TIME OF APPLICATION ON YIELD AND QUALITY OF NO-TILL WINTER WHEAT

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ABSTRACT

The introduction of a practical snow management system, which utilizes no-till seeding into standing stubble immediately after harvest of the previous crop ("stubbling-in") has allowed for expansion of the North American winter wheat (Triticum aestivum L.) production area to include most of the western Canadian prairies. Soil nitrogen (N) deficiencies are usually associated with this production system and N fertilization is normally required to maximize grain yield and maintain acceptable grain quality. The present study summarizes twenty-one broadcast ammonium nitrate fertilizer field trials conducted from 1976 to 1986 in Saskatchewan with the objectives of determining the effect of date of N fertilizer application on grain yield, grain protein yield and grain protein concentration of stubbled-in hard red winter wheat. Dates of N application considered were early fall, late fall, early spring and late spring. Date of N application had significant influence on total grain yield, grain protein yield and grain protein concentration in 33, 33 and 29% of the trials, respectively. Reduced grain and grain protein yields, attributed primarily to denitrification losses, and immobilization, were observed with fall N applications in four trials located in the northeastern part of the agriculture region of Saskatchewan. Reductions in grain protein concentration accompanied these N losses. In contrast, a prolonged dry period, following spring N applications resulted in a temporary stranding of fertilizer N on the soil surface at one location thereby delaying its availability to the plant until after early spring N deficiencies had seriously limited the yield potential of the crop. Delays in N application had the same effect. Reduced grain and grain protein yield and increased grain protein concentration were also observed for fall and early spring N applications in trials that experienced spring environmental conditions favorable to plant growth followed by prolonged drought. This sequence of environmental conditions resulted in maximum grain protein concentrations that ranged from 14.5 to 20% compared to approximately 13% under normal growing conditions for this region.

An additional nine field trials were conducted from 1982 to 1986 with the objectives of determining the influence of fertilizer formulation and placement method on N response of stubbled-in winter wheat. Reduced grain and grain protein yield responses indicated large N losses due to volatilization of broadcast urea in three of the nine trials. Comparison with yield response curves for ammonium nitrate indicated that the losses with broadcast urea could be in excess of 50% of the added N. Fall banding prior to seeding was effective in reducing losses with urea, but did not outperform broadcast ammonium nitrate applied at the same time. Yield losses, which were probably due to denitrification, were observed for both urea and ammonium nitrate broadcast in the late fall at one location.

INTRODUCTION

In recent years, the introduction of 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 promise for expanding winter wheat production in western Canada (Fowler, 1983). Most stubble fields are deficient in available soil nitrogen (N) with the result that N fertilization is usually required to maximize grain yield (Fowler et al., 1988a) and maintain acceptable grain protein concentrations (Fowler et al., 1988b). The maintenance of standing stubble is mandatory for adequate snow-trap and the successful overwintering of wheat in Saskatchewan, therefore minimum soil disturbance and stubble breakdown in the fall are prerequisites to this management system. The introduction of winter wheat into a traditional spring crop region has also raised questions as to the importance of timing of N applications to maximize fertilizer use efficiency. As expected, environment and crop have a large influence in determining the optimum time for N application. Several studies in other regions and/or crops have found little or no difference in grain yield due to time of N fertilizer application (Ramig and Rhoades, 1963; Stanford and Hunter, 1973; Hunter and Stanford, 1973; Christensen and Meints, 1982; Kucey and Schaalje, 1986). In contrast, date of N fertilization has been shown to influence grain yield and protein concentration, and many researchers have concluded that spring-applied N leads to greater uptake (Hunter and Stanford, 1973; Ellen and Spiertz, 1980; Olson and Swallow, 1984). The objectives of the rate and date study were to determine the effect of date of N fertilizer application on grain yield, grain protein yield and grain protein concentration of stubbled-in hard red winter wheat produced in Saskatchewan.

The amount of fertilizer N available to the plant is influenced by the degree of immobilization, denitrification, ammonia volatilization, and leaching that takes place after application. With the exception of chemical fallow, soil moisture is usually deficient with the stubbling-in production system in western Canada with the results that leaching is not likely to be a problem. Maintenance of standing stubble is a critical factor in overwintering wheat. The decay of this crop residue can result in an immobilization of N making it temporarily unavailable to the growing crop (Olson and Swallow, 1984). Anaerobic conditions leading to denitrification may also be especially prevalent under the stubbling-in type of production system where a lack of cultivation leads to a densely packed surface horizon with a high bulk density. Aulakh et al. (1982) found that gaseous N losses due to denitrification under a no-till system were twice those of a conventionally tilled system. In addition, urea may be especially vulnerable to volatilization losses when broadcast on surface residues (Jensen, 1982; Keller and Mengel, 1986; McInnes et al., 1986). Fall-banding of urea has been shown to be more effective in reducing volatilization losses (Nyborg and Malhi, 1979; Carter and Rennie, 1984) and increasing crop yields (Malhi and Nyborg, 1985). However, limited time between harvest of the previous crop and seeding, combined with seedbed damage and increased stubble break-down, restrict the banding options that are practical with the stubbling-in management system for winter wheat produced in Saskatchewan (Fowler, 1983). With these potential problems in mind, the method and formulation study was initiated to determine the effect of N fertilizer formulation and placement method on the N response of grain yield, grain protein yield, and grain protein concentration of stubbled-in hard red winter wheat in Saskatchewan.

MATERIALS AND METHODS

Rate and Date

Twelve date and rate of N fertilizer application trials were conducted from 1976 to 1986 in Saskatchewan, Canada (Table 1). Experimental design for the years 1976 to 1978 was a split plot with N fertilizer rate as the main plots and date of N application as the sub-plots. Experimental design for all subsequent trials was a split plot with date of N application as the main plots and rate of N application as the sub-plots. Nitrogen treatments were replicated four times in each trial. Nitrogen treatments were applied in early fall, late fall, early spring and, in several trials, late spring (Table 1). Fertilizer rates were 0, 34, 67 and 101 kg N ha^{-1}; additional rates of 202 kg N ha^{-1} were added at some sites (Table 1).

An additional nine modified date and rate of N fertilizer trials were conducted in Saskatchewan in 1981-82 and 1982-83 (Table 1). Experimental design for these trials was a randomized complete block with three replicates. Fertilizer rates were 0, 34, 67 and 101 kg N ha^{-1} applied in early spring. Treatments of 67 and 101 kg N ha^{-1} were added in early fall, late fall and late spring of 1981-82 and 1982-83, respectively (Table 1).

The most highly adapted winter wheat cultivars for this region were utilized in these trials. 'Sundance' was the top performing winter wheat cultivar available prior to 1978. The release of 'Norstar' provided a cultivar with superior winter hardiness and grain quality. Consequently, Sundance was replaced by Norstar in all trials after 1978. These two cultivars have similar grain yield and protein concentration when produced in Saskatchewan (Fowler and de la Roche, 1984).

All trials were direct seeded into standing stubble (Table 1) immediately after harvest of the previous crop (between 24 August and 7 September of each year).

Method and Form

A total of nine N fertilizer formulation and placement method trials were conducted in the Brown, Dark Brown, and Black Chernozemic soil zones in Saskatchewan, during the years 1982 to 1986 (Table 2). Experimental design for all trials was a split split plot with N fertilizer form as the main plots, placement methods and dates as the sub-plot and N rate as the sub-sub-plots. Fertilizer forms included ammonium nitrate (34-0-0) and urea (46-0-0). Placement methods and dates for both N forms included band and broadcast treatments applied immediately prior to seeding, and broadcast treatments applied in the late fall and early spring (Table 2). Fertilizer bands were placed perpendicular to the direction of seeding at a depth of approximately 8 cm and a spacing of 30 cm. Fertilizer rates were 0, 34, 67 and 101 kg N ha^{-1}.

In all trials, 'Norstar' winter wheat was direct seeded into standing stubble with a commercial minimum tillage drill immediately after harvest of the previous crop (between 24 August and 7 September of each year).

Table 1. Test location, previous crop, soil characteristics, dates of N fertilizer application and general environmental conditions for date of fertilizer trials.

			Soil			Date of N application (day/mon)				
Location	Year	Previous Crop†	Classification‡	Texture‡	NO_3-N in Early spring (kg N ha^{-1})	Early fall	Late fall	Early spring	Late spring	Environmental conditions§
A) Rate and Date Experiments										
1.Clair	1976-77	Rapeseed	Udic Haploboroll	L	54	15/9	10/10	3/5	2/6	Good
2.Saskatoon	1976-77	Rapeseed	Vertic Haploboroll	SiCL	220	14/9	9/10	2/5	1/6	Average
3.Clair	1977-78	Barley	Udic Haploboroll	L	19	10/9	15/10	1/5	1/6	Good
4.Clair	1982-83	Winter Wheat	Udic Haploboroll	L	43	5/9	17/10	1/5		Average
5.Kindersley	1982-83	Winter Wheat	Aridic Haploboroll	CL	47	30/8	14/10	3/5		Poor
6.Watrous	1982-83	Winter Wheat	Typic Haploboroll	L	33	31/8	13/10	3/5		Average
7.Clair	1983-84	Rapeseed	Udic Haploboroll	L	22	2/9	19/10	20/4		Good
8.Saskatoon	1983-84	Rapeseed	Vertic Haploboroll	C	103	8/9	14/10	30/4		Poor
9.Strasbourg	1983-84	Winter Wheat	Typic Haploboroll	L	19	29/8	12/10	28/4		Poor
10.Watrous	1983-84	Winter Wheat	Typic Haploboroll	CL	33	29/8	12/10	28/4		Average
11.Strasbourg	1984-85	Flax	Typic Haploboroll	L	58	1/9	3/10	29/4		Poor
12.Clair	1985-86	Barley	Udic Haploboroll	L	47	3/9	1/10	25/4		Average
B) Modified Rate and Date Experiments										
13.Saltcoats	1981-82	Barley	Udic Haploboroll	L	79	28/8	6/10	4/5	29/5	Average
14.Kipling	1981-82	Winter Wheat	Typic Haploboroll	L	47	27/8	6/10	5/5	28/5	Poor
15.Langbank	1981-82	Winter Wheat	Typic Haploboroll	L	28	28/8	6/10	6/5	28/5	Poor
16.Carnduff	1981-82	Durum Wheat	Udic Haploboroll	L	62	26/8	5/10	7/5	28/5	Poor
17.Wynyard	1981-82	Spring Wheat	Udic Haploboroll	L	57	3/9	6/10	3/5	29/5	Good
18.Meadow Lake	1982-83	Rapeseed	Udic Agriboroll	C	29	10/9	6/10	5/5	1/6	Poor
19.Kelvington	1982-83	Barley	Udic Haploboroll	L	155	2/9	17/10	8/5	2/6	Average
20.Nipawin	1982-83	Rapeseed	Boralfic Agriboroll	FSL	39	2/9	7/10	6/5	9/6	Average
21.Paddockwood	1982-83	Rapeseed	Boralfic Agriboroll	L	71	6/9	5/10	6/5	2/6	Average

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†Rapeseed (*Brassica campestris* L.), Barley (*Hordeum vulgare* L.), winter and spring wheat (*Triticum aestivum* L.), Flax (*Linum usitatissimum* L.).

‡Soil Survey Staff. 1975. Soil Taxonomy, Agric. Handbook No. 436. U.S. Government Printing Office, Washington, D.C. L - Loam, Si - Silty, C - Clay, F - Fine, S - Sandy.

§Good - Above average rainfall that was well distributed during the growing season. Moisture reserves adequate to cope with wind and heat stress experienced.

Average - No extended dry periods. Head and/or wind stress may have been yield-reducing factors. Average growing season rainfall for this area

Poor - Periodic drought combined with heat and/or wind stress.

General

In both the rate and date, and method and form trials, phosphate fertilizer (11-55-0 or 11-48-0) was applied with the seed at rates recommended for each soil type. Elements other than phosphorus and nitrogen were not considered limiting. Nitrogen fertilizer plots were 5.5 m long and 1.2 m wide with 30 cm unfertilized between plots. Grain yield was determined from a five m long and one m wide sample that was harvested from each plot at maturity.

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 (Tables 1 and 2).

In the early spring of each year, mid-row soil samples were collected from the surface 60 cm (from plots that had not received N fertilizer) of each trial site for nutrient analyses by the Saskatchewan Institute of Pedology, soil testing laboratory. Available NO_3-N levels were determined colorimetrically by auto analyzer using cadmium reduction (Technicon Industrial Method #100-70W, Technicon Instrument Corp., Tarrytown, N.Y.). Soil and fertilizer N were considered to be equally plant available. Therefore, total available N was calculated for each treatment as the sum of available soil N to 60 cm depth, as estimated from the soil test, and added fertilizer N (Heapy et al., 1976; Zentner and Read, 1977; France and Thornley, 1984; Bole and Dubetz, 1986.).

Grain protein concentration and protein yield (grain yield x protein concentration) were determined for each plot in each trial. Protein concentrations were determined from Kjeldahl N (N x 5.7) or by the Udy dye method (Udy, 1971). Kjeldahl analyses were utilized to standardize protein concentrations in each trial analyzed by the Udy dye method.

Analyses of variance were conducted to determine the significance of treatment differences within each fertilizer trial. 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 has been elaborated on in earlier publications (Fowler et al., 1988a; b).

The inverse polynomial equation takes the form:

$$Y = \frac{uN}{N + u/e} \quad (1-N/s), \qquad (1)$$

where Y = predicted grain or protein yield (kg ha^{-1})
N = total available N (kg N ha^{-1})
s = sensitivity to high N levels, larger s indicates less sensitivity
u = upper limit of yield achieved in the absence of sensitivity to high levels of N
e = maximum N use efficiency at low levels of N

Table 2. Test location, previous crop, soil characteristics, dates of N fertilizer application and general enviromental conditions for N formulation and method of application trials.

	Location	Year	Previous Crop†	Soil			Date of application (day/mon)			Environmental§ conditions
				Classification‡	Texture	NO_3-N in early spring (kg N ha^{-1})	Early fall	Late fall	Early spring	
1.	Clair	1982-83	Winter wheat	Udic Haploboroll	L	43	5/9	17/10	1/5	Average
2.	Kindersley	1982-83	Winter wheat	Aridic Haploboroll	CL	47	30/8	14/10	3/5	Poor
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4.	Clair	1983-84	Rapeseed	Udic Haploboroll	L	22	2/9	19/10	20/4	Good
5.	Saskatoon	1983-84	Rapeseed	Vertic Haploboroll	C	103	8/9	14/10	30/4	Poor
6.	Strasbourg	1983-84	Winter wheat	Typic Haploboroll	L	19	29/8	12/10	28/4	Poor
7.	Watrous	1983-84	Winter wheat	Typic Haploboroll	CL	33	29/8	12/10	28/4	Average
8.	Strasbourg	1984-85	Flax	Typic Haploboroll	L	58	1/9	3/10	29/4	Poor
9.	Clair	1985-86	Barley	Udic Haploboroll	L	47	3/9	1/10	25/4	Average

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

‡ Soil Survey Staff. 1975. Soil Taxonomy, Agric. Handbook No. 436. U.S. Government Printing Office, Washington, D.C. L-Loam, C-Clay.

§ Good-Above average rainfall that 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. Average growing season rainfall for this area 208 to 278 mm.
Poor-Periodic drought combined with heat and/or wind stress.

Non-linear regression procedures outlined by the SAS Institute (1985) were used to provide least-squares estimates of the regression coefficients u, e and s. In some cases, the limited data prevented the statistical program from converging on reasonable estimates of all three coefficients. In these instances, s was held constant at the value (903 for grain and 949 for grain protein yield) determined in earlier studies (Fowler et al., 1988a) and u and e were successfully estimated.

The Gompertz equation takes the form:

$$P = M + A \exp\left[-B \exp(-KN)\right] \qquad (2)$$

where P = predicted protein concentration (%)
M = minimum protein concentration (%)
$M + A$ = asymptotic protein concentration achieved at high N levels
B = determines N level at which protein concentration reaches $M + 0.5A$
K = coefficient that determines the rate P increases to M+A.
N = total available N (kg ha^{-1}).

The coefficients K and M were held constant at 0.02302 and 8.2, respectively (Fowler et al., 1986b). Non-linear regression procedures outlined by the SAS Institute (1985) were used to provide least-squares estimates of the coefficients A and B.

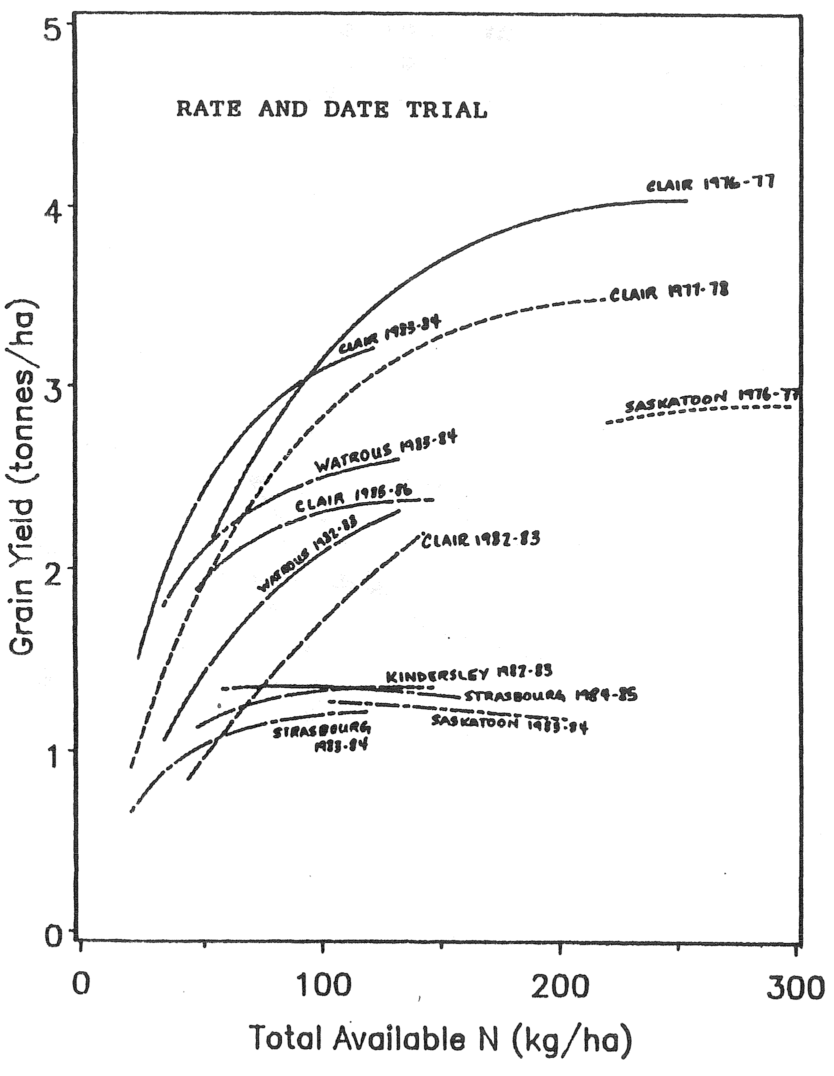
RESULTS AND DISCUSSION

Rate and Date

The 21 site-years considered in this study represented a wide range of soil types and environmental conditions (Table 1). When nutrient deficiencies had been corrected, and in the absence of obvious disease problems, maximum grain yields ranged from in excess of 4 tonnes ha^{-1} at Clair in 1976-77 to 0.75 tonne ha^{-1} at Meadow Lake in 1982-83 (Fig. 1 and 2). This wide range in realized grain yield could be mainly attributed to differences in mid- and late-season moisture or related stresses (Fowler et al., 1988a).

There is a very strong positive relationship between grain and grain protein yield (Fowler et al., 1988b). This relationship was evident in the rate and date studies and similar N rate response patterns were observed for grain and grain protein yield. Early spring applications of N gave significant ($P \leq 0.05$) rate responses for both grain and grain protein yield in all trials except Saskatoon 1976-77 and 1983-84 (Figs. 1,2,3 and 4). Residual soil N was exceptionally high at Saskatoon in 1976-77 and a severe late season drought in 1983-84 limited grain yield responses in these Saskatoon trials (Table 1). With the exception of Kipling 1981-82 and Strasbourg 1984-85 (Fig. 1,2,3 and 4), the observed yield responses to increased N were all positive. The significant ($P \leq 0.05$) grain and grain protein yield reductions observed with increased N at Strasbourg 1984-85 and Kipling 1981-82 were associated with favorable early spring growing conditions followed by a severe extended drought.

The inverse polynomial function (Equation 1) outlined by France and Thornley (1984) provided a curvilinear yield - N fertilizer response surface that conformed well with the general grain (Fig. 1 and 2) and grain protein (Fig. 3 and 4) yield trends observed in the field data from these trials.



gure 1. Grain yield response to total available N for early spring N fertilizer application in rate and date experiments.

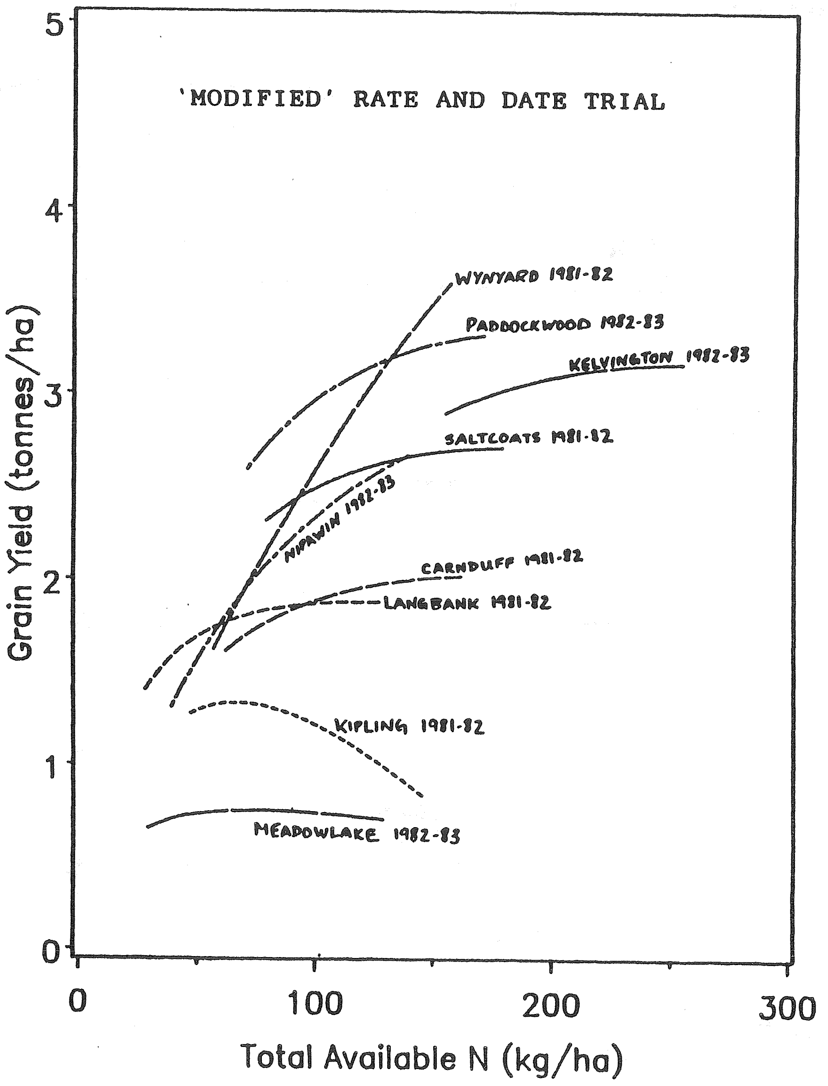


Figure 2. Grain yield response to total available N for early spring N fertilizer application in modified

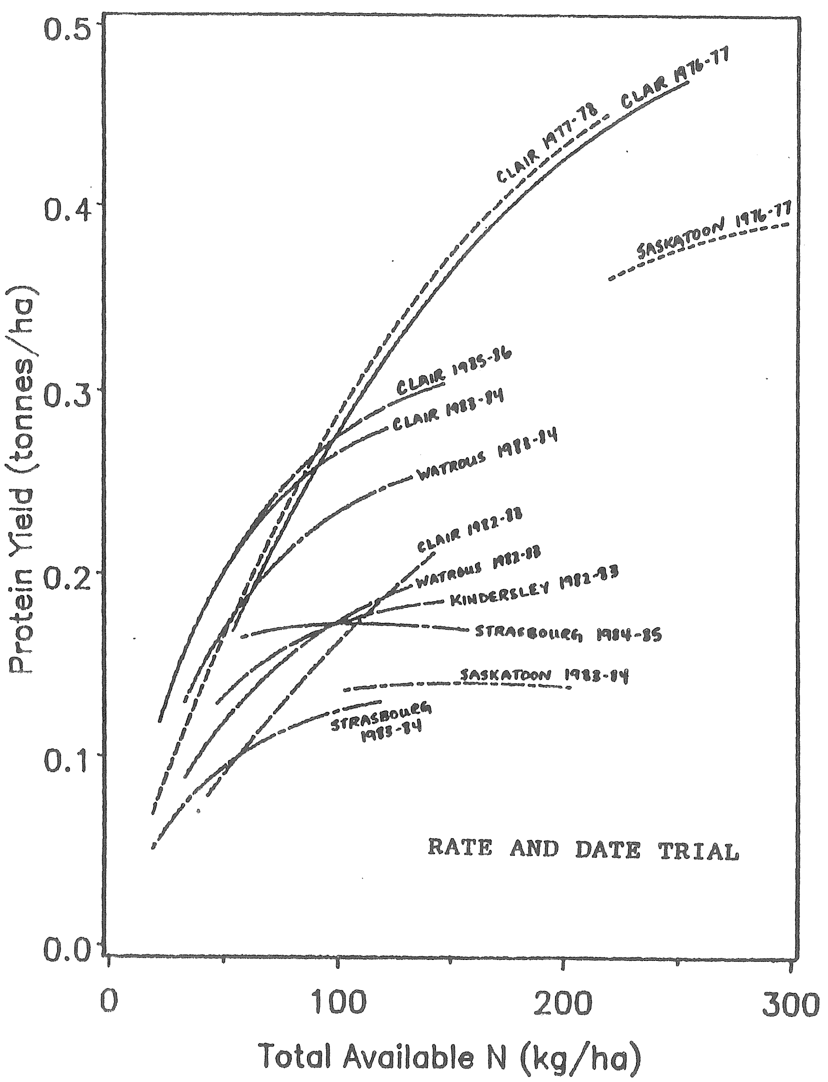


Figure 3. Grain protein yield response to total available N for early spring N fertilizer application in rate and date experiments.

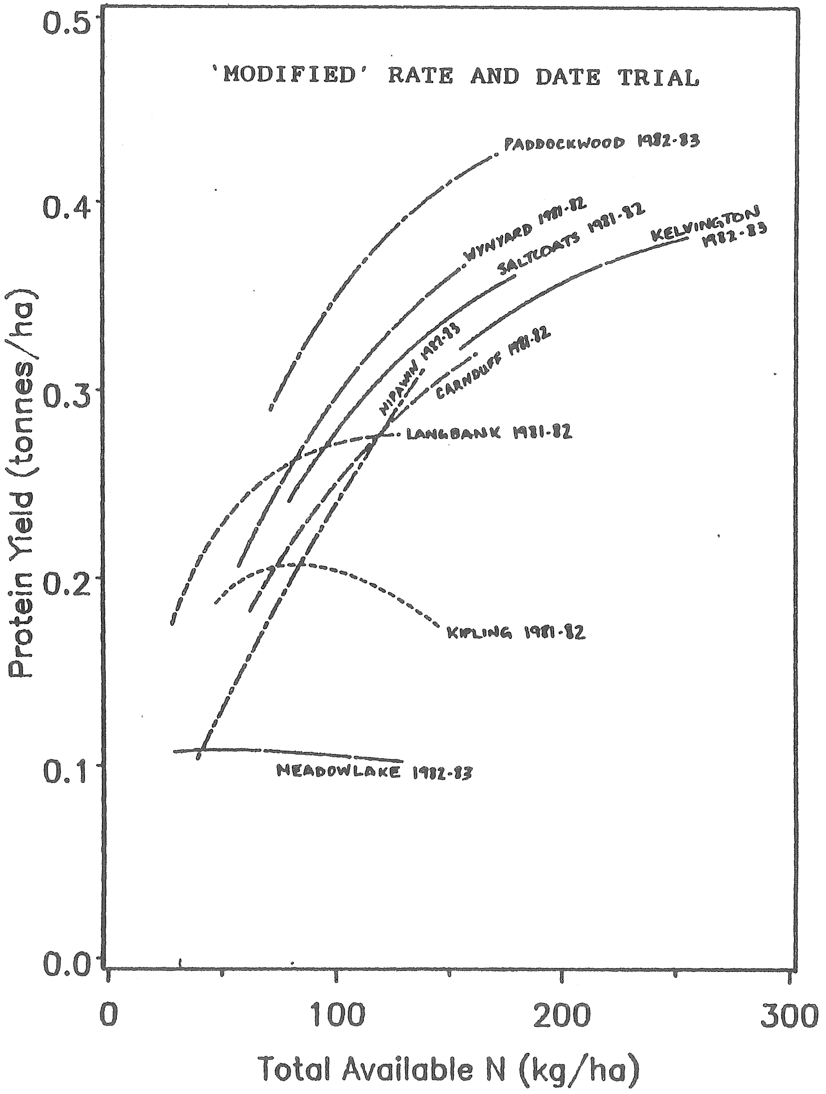


Figure 4. Grain protein yield response to total availabl N for early spring N fertilizer application in modified rate and date experiments.

Predicted yields from these equations accounted for 99.6 and 99.3% of the pooled variability in actual grain and grain protein yields, respectively. The regression coefficients for the equations that best described grain and grain protein yield responses for each rate and date of N application are given in Tables 3 and 4.

Date of N application had a significant ($P \leq 0.05$) influence on both grain yield (Fig. 5) and grain protein (Fig. 6) yield in seven of the 21 trials considered. All seven of these trials had residual soil-N levels that fall below 60 kg ha^{-1} (Table 1). Theoretically, maximum grain and grain protein yield responses to added N should be constant at a given location as long as sufficient fertilizer was applied before N became limiting to plant growth. Loss, or immobilization, of fertilizer N should then be indicated by reduced N-use efficiency for yield and a horizontal "lag" or a shift of the response curve to the right. Comparisons with early spring N response curves suggest that this type of reduced N-use efficiency, probably due to denitrification losses (Malhi and Nyborg, 1983), occurred for early and late fall applications at Clair 1977-78 and Nipawin 1982-83, and late fall applications at Clair 1982-83 (Fig. 5 and 6). All of these sites were located in north-eastern Saskatchewan, a region that tends to be cool and relatively damp in the fall and spring. Similar yield reductions were observed for early fall N applications at Clair 1976-77. However, the absence of yield losses for late fall N applications in this trial suggests that the poor performance for early fall applications may have been at least partially due to N immobilization (Olson and Swallow, 1984). As a practical example of the magnitude of the losses observed in these trials, 100 kg N ha^{-1} applied in the early fall at Clair 1976-77 (a) early and late fall at Clair 1977-78 (b) and (c) and Nipawin 1982-83 (d) and (e) and the late fall at Clair 1982-83 (f) produced grain (grain protein) yields that were equal to those produced by a) 78(87), b) 64(69), c) 81(69), d) 73(72), e) 73(72), and f) 88(77) kg N ha^{-1} broadcast in the spring, respectively.

Late spring N applications (approximately two weeks before anthesis, Table 1) produced limited or no improvement in grain yield at five out of five sites (Fig. 5) at which date of N application had a significant influence (note: late spring applications were not made at Clair 1982-83 and Kindersley 1982-83). In contast, these same treatments resulted in comparatively larger increases in grain protein yield at all five sites (Fig. 6). Cereal protein contains approximately 17.5% N. Beacuse this N is obtained from the soil, plant-available soil N has a direct influence on grain protein yield. Conversely, grain protein yield provides a direct measure of the relative plant-available soil N produced by treatments in fertilizer trials. Consequently, the larger increases in grain protein N yield relative to increases in total grain yield, with late spring N applications, indicates that while N uptake continues well into the growing season N deficiencies should be corrected by early spring to maximize grain yield response in Saskatchewan.

At Kipling 1981-82, increasing N rate decreased yield except for late spring applications where the check yield was maintained even at high N rates (Fig. 5). This observation also indicates that the N from late spring fertilizer applications was not available before N became severely limiting to plant growth. In the absence of N-stimulated luxuriant spring growth, plants in late spring applied N plots did not sustain the same level of damage ("haying off"), from the subsequent extended drought, as plants in

Table 3. Estimated regression coefficients for grain yield in Equation 1 for rate and date trials.

Location[†]	Nitrogen[‡] Application Date	u	e	s
1	EF	7747	52	903
	LF,ES	9137	58	903
	LS	4528	67	903
2	All	8207	31	903
3	EF	4295	61	903
	LF	4809	71	903
	ES	7402	56	903
	LS	2734	80	903
4	EF,ES	16667	22	903
	LF	10856	21	903
5	EF,LF	3420	45	903
	ES	1938	66	903
6	All	5324	42	903
7	All	5372	99	903
8	All	1502	204	1085
9	All	1762	58	903
10	All	3293	123	2737
11	All	1666	174	903
12	All	3575	96	903
13	All	4605	72	903
14	EF,LF,ES	3412	66	217
	LS	2293	66	903
15	All	2553	119	903
16	All	3336	58	903
17	EF,LF,ES	32698	32	903
	LS	7006	32	903
18	All	1091	66	465
19	All	7444	43	903
20	EF,LF,LS	4443	44	903
	ES	6491	44	903
21	All	6022	75	903

[†] See Table 1 for actual locations.

[‡] EF - early fall, LF - late fall, ES - early spring, LS - late spring. See Table 1 for exact dates.

Table 4. Estimated regression coefficients for grain protein yield in Equation 1 for rate and date trials.

Location[+]	Nitrogen[*] Application Date	u	e	s
1	LS	1003	4.1	949
	EF	1648	3.3	949
	LF,ES	2119	3.6	949
2	All	1449	3.2	949
3	EF,LF,LS	610	3.9	949
	ES	1953	3.8	949
4	EF,ES	1917	2.0	949
	LF	783	1.8	949
5	EF,LF	483	4.3	949
	ES	309	5.1	949
6	All	435	3.5	949
7	All	504	7.3	949
8	All	209	5.6	949
9	All	235	3.5	949
10	All	485	5.7	949
11	All	224	14.0	949
12	All	562	6.8	949
13	All	979	4.6	949
14	EF,LF,ES	477	8.9	292
	LS	415	8.9	949
15	All	439	11.2	732
16	All	969	4.0	949
17	EF,LF,ES	1024	4.9	949
	LS	662	4.9	949
18	All	121	45.6	949
19	All	1070	3.8	1023
20	EF,LF	697	2.8	949
	ES	5074	2.8	949
	LS	1253	2.8	949
21	All	985	6.5	949

[+] See Table 1 for locations

[*] EF - early fall, LF - late fall, ES - early spring, LS - late spring. See Table 1 for exact dates.

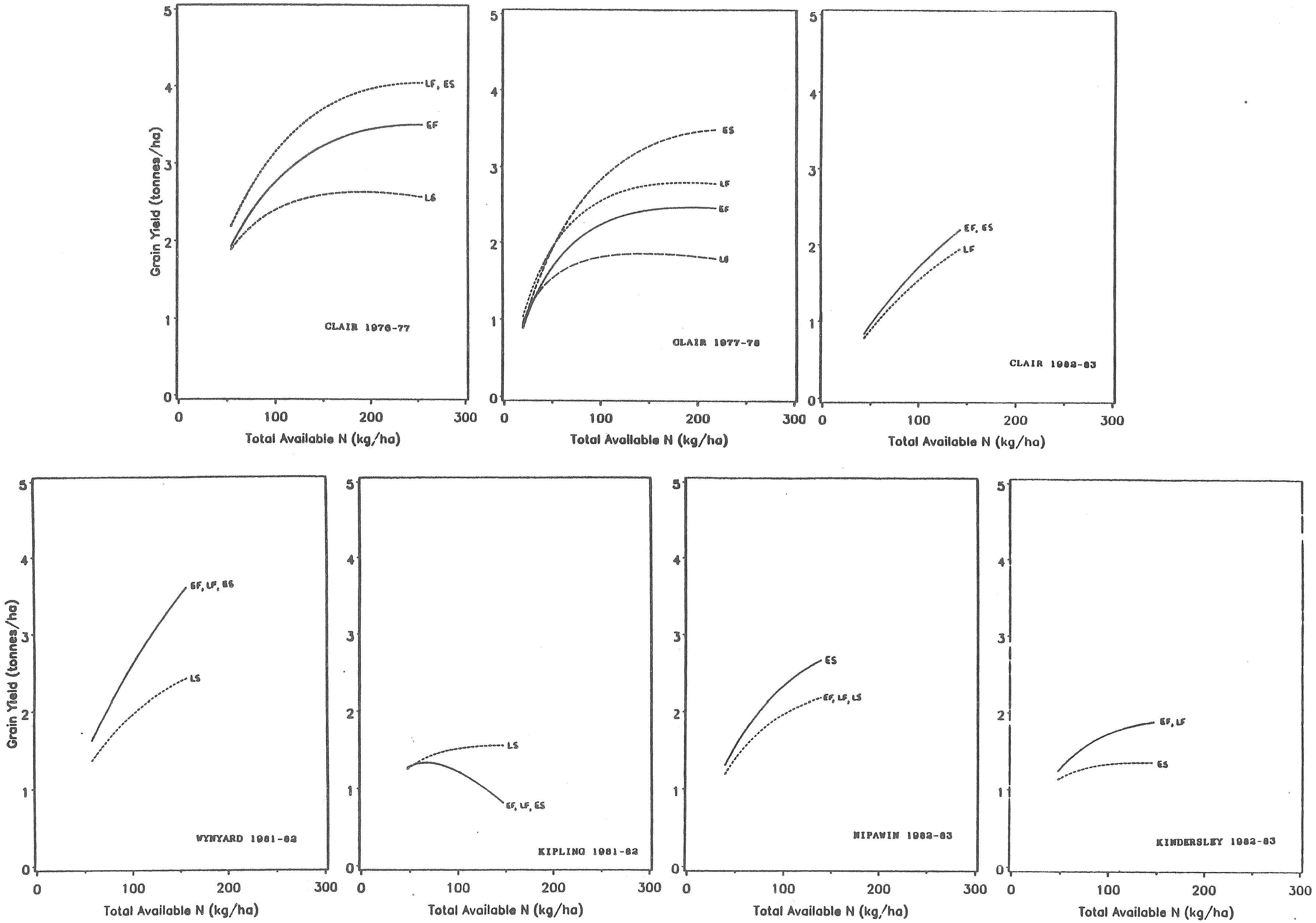


Figure 5. Grain yield response to total available N for

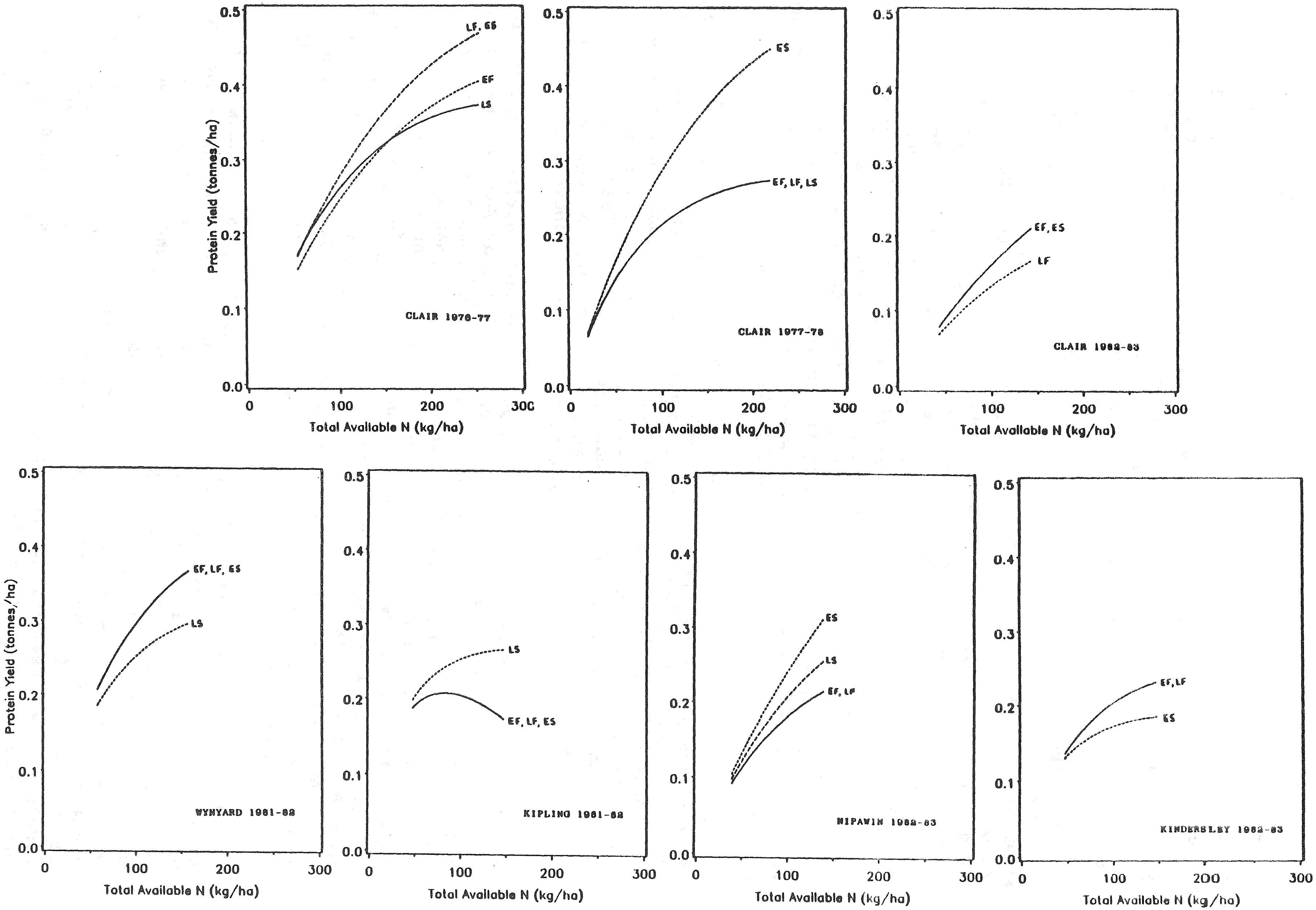


Figure 6. Grain protein yield response to total available N for locations where significant differences due to date of N application were observed.

plots with high levels of available N from earlier fertilizer applications. Reductions in grain protein yield were also associated with early N applications in this trial. This suggests that, while N uptake most certainly occurred early in the season, the resulting drought-induced sensitivity to high levels of N also interfered with N translocation to the developing seed.

Early spring N applications resulted in significant ($P \leq 0.05$) rate responses for grain protein concentration in 18 out of 21 trials in this study (Fig. 7 and 8). It is noteworthy that protein concentration N responses were detected in trials at Saskatoon 1976-77 and 1983-84 where added N did not result in measurable changes in grain or grain protein yield. This inconsistency was probably due to the fact that the N requirement for maximum grain protein yield is considerably higher than for maximum grain yield (Fowler et al., 1988b). Consequently, although significant differences were not detected, the rates of change for grain and grain protein yield were different, especially in 1976-77 (Fig. 1 and 3), with the result that significant ($P \leq 0.05$) differences were detected in protein concentration (Fig. 7). Only the trials at Clair 1982-83 and 1983-84, and Watrous 1982-83 did not produce a significant ($P \geq 0.05$) increase in protein concentration with added N fertilizer (Fig. 7).

The Gompertz equation (Equation 2) provided an excellent description of the relationship between protein concentration and total plant-available N (Fig. 7 and 8). Predicted protein concentrations from these equations (Table 5) accounted for 97.6% of the pooled variability in actual grain protein concentration. The slope of this N-response curve includes a lag phase, an increase phase, and a tailing off phase (Fowler et al., 1988b). The length of the lag phase of the curve is a reflection of the total N required to produce a significant increase in grain protein concentrations above 8.2%.

In the rate and date study the lag phase for early spring N applications varied from a B value of practically zero (B = 0.46) at Meadow Lake 1982-83 to greater than 70 at Clair 1982-83, 1983-84 and Watrous 1982-83 (Table 5). These three trials that produced extremely long lag phases (Table 5) were the same three trials that did not produce a measurable increase in protein concentration in the range of added N considered. In fact, a decrease in protein concentration was observed for at least the first two increments of added N in these trials. An inability to accommodate this initial decrease is an obvious deficiency in the equation utilized to describe the response of protein concentration to added fertilizer N and is an area that deserves further investigation.

An initial depression in the protein concentration N response curve has been noted in other studies (Partridge and Shaykewich, 1972; Bole and Dubetz, 1986) and is usually associated with cool, wet spring conditions. The spring of 1982-83 was particularly cool and damp until the end of May at both Clair and Watrous. Similar conditions were also experienced at Clair in 1983-84 where snow and cool damp weather in early May resulted in a delay in the seeding of spring crops. The long lag phase in the protein concentration N response curves (Fig. 7) for these locations suggest that there may have been significant N losses for all fertilizer dates considered. Late spring application dates may have provided some indication of the occurrence of N losses for earlier application dates but, unfortunately, this date was not included in these trials.

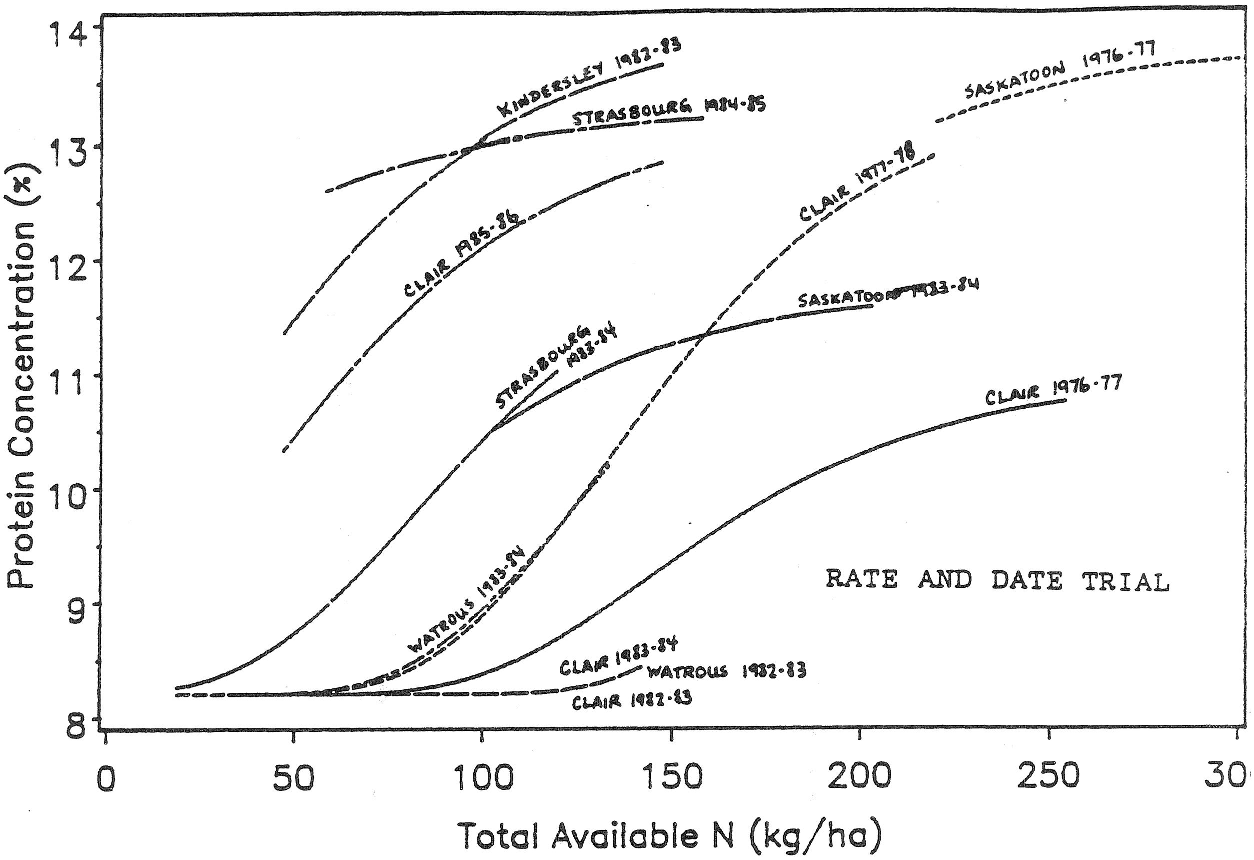


Figure 7. Grain protein concentration response to total available N for early spring N fertilizer application in rate and date experiments.

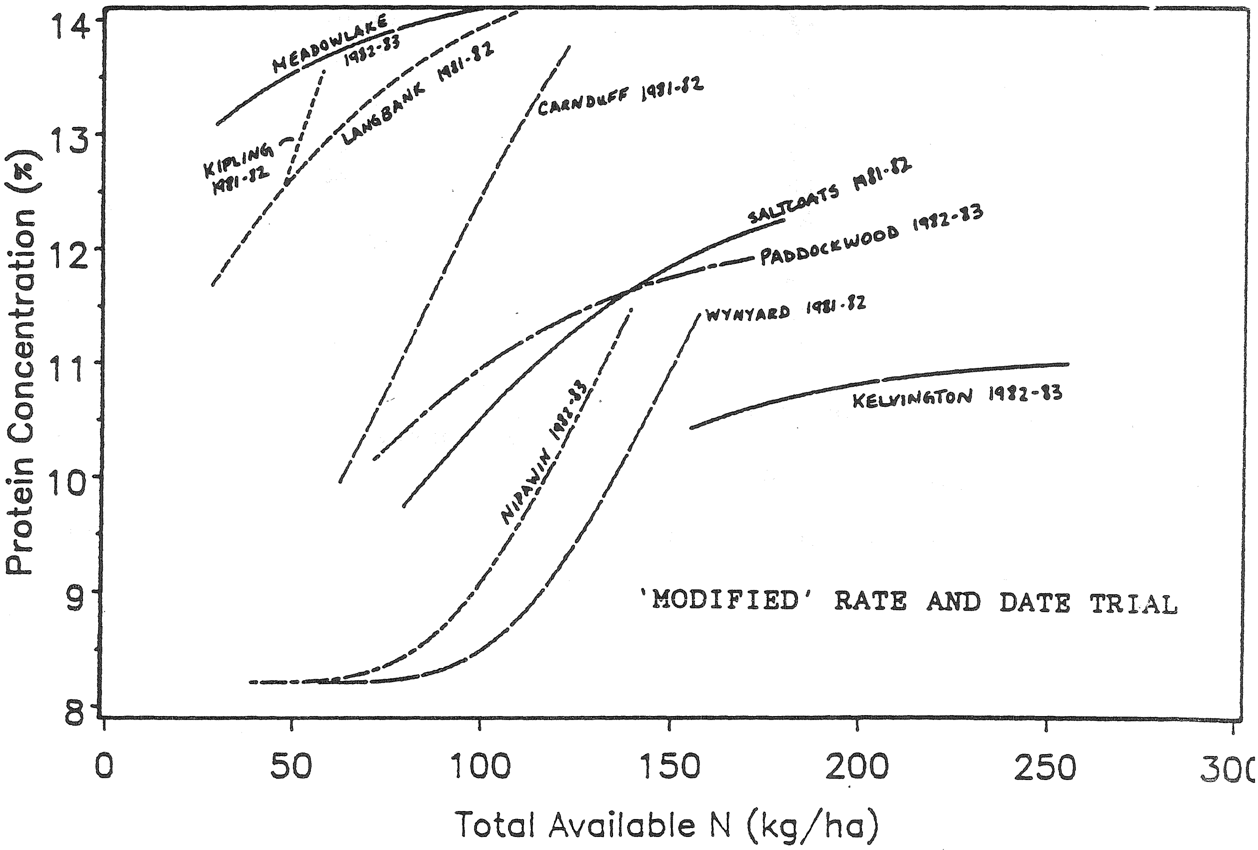


Figure 8. Grain protein concentration response to total available N for early spring N fertilizer application in modified rate and date experiments.

Table 5. Estimated regression coefficients for grain protein concentration in equation 2 for rate and date trials.

Location[†]	Nitrogen[‡] Application Date	A[††]	B
1	EF,LF,ES	2.74	27.37
	LS	4.89	6.74
2	All	5.58	19.18
3	EF	3.63	19.10
	LF	1.95	19.02
	ES	5.34	20.55
	LS	5.08	9.79
4	All	N/A	> 70
5	EF,LF	4.15	1.23
	ES	5.78	1.79
6	All	N/A	> 70
7	All	N/A	> 70
8	All	3.52	4.50
9	All	4.32	6.62
10	All	4.71	18.45
11	EF,LF	4.95	0.75
	ES	5.04	0.52
12	All	5.05	2.56
13	All	4.50	6.61
14	EF,LF,ES	11.66	2.90
	LS	10.42	2.90
15	All	6.46	1.18
16	All	8.19	6.44
17	EF,LF,ES	7.85	33.05
	LS	7.85	24.61
18	All	6.18	0.46
19	All	2.86	8.95
20	EF,LF	8.06	46.51
	ES,LS	8.06	22.16
21	All	3.99	3.69

[†] See Table 1 for actual locations

[‡] EF - early fall, LF - late fall, ES - early spring, LS - late spring. See Table 1 for exact dates.

[††] N/A Maximum N rates applied were not high enough to provide an estimate of A.

Values of A (Table 5) ranged from 2.74 to 11.66 for early spring N applications indicating considerable variability in maximum protein concentration due to environmental factors (Fig. 7 and 8). Trials that yielded A values greater than 5.8 (Kipling, Langbank and Carnduff 1981-82 and Meadow Lake 1982-83) all experienced favorable early season growing conditions, until near the end of May, followed by high evaporation and very low rainfall through June and into early July.

Date of fertilizer application had a significant ($P \leq 0.05$) influence on grain protein concentration in 6 out of 21 trials considered (Fig.9). Early spring N applications resulted in grain protein concentrations that were equal to or greater than fall applications in all 6 of these trials. At Clair 1977-78 and Nipawin 1982-83, early spring N applications also yielded as much or more grain (Fig.5) and grain protein (Fig. 6) as the fall applications. However, a faster rate of increase in grain than grain protein yield resulted in lower protein concentrations and a shift of the N response curve to the right for at least one of the fall application rates at these locations (Fig. 9).

Where comparisons could be made, late spring N applications resulted in grain protein concentrations that were equal to or greater than those for early spring N applications in all trials except for Kipling 1981-82 (Fig.9). Late spring N applications produced significantly ($P \leq 0.05$) higher protein concentrations than all other application times at Clair 1976-77, 1977-78 and Wynyard 1981-82. All three were high moisture sites (Table 1) and it appears that the late spring applied N was available to the winter wheat only after early spring N deficiencies had seriously limited the yield potential of the crop. This resulted in grain protein N yield responses (Fig. 6) that were greater than those for grain yield (Fig. 5) and higher grain protein concentrations (Fig. 9) for late spring N applications. A similar situation was indicated for the dry spring at Kindersley 1982-83, where it appears that early spring applied N was also positionally unavailable until after N deficiencies had limited yield potential (Fig. 5). Rainfall was not received from the time of early spring N application (Table 1) until 18 June at Kindersley 1982-83. Although the spring applied N was not available in time to greatly influence grain yield at this location (Fig. 5), it did have a larger effect on protein yield (Fig.6). The result of this temporary stranding of N was higher protein concentrations for the early spring application.

The protein concentrations for late spring N applications were lower than for earlier application dates only at Kipling 1981-82. This was also the only location that experienced both grain (Fig. 5) and grain protein (Fig. 6) yield reductions with added N for all but the late spring application. In this instance, the late spring applied N was also taken up too late to have a large influence on plant dry matter accumulation and yield. However, as indicated earlier, in the absence of N-stimulated luxuriant spring growth, late spring applied N plots did not sustain as much damage from the subsequent extended drought as plants in plots with high levels of available N from earlier fertilizer applications. The net result was higher grain yields (Fig. 5) that produced a greater dilution of the grain protein and lower protein concentration (Fig. 9) for the late spring N applications.

In summary, the results of this study demonstrate that date of N fertilizer application can have a significant influence on grain yield,

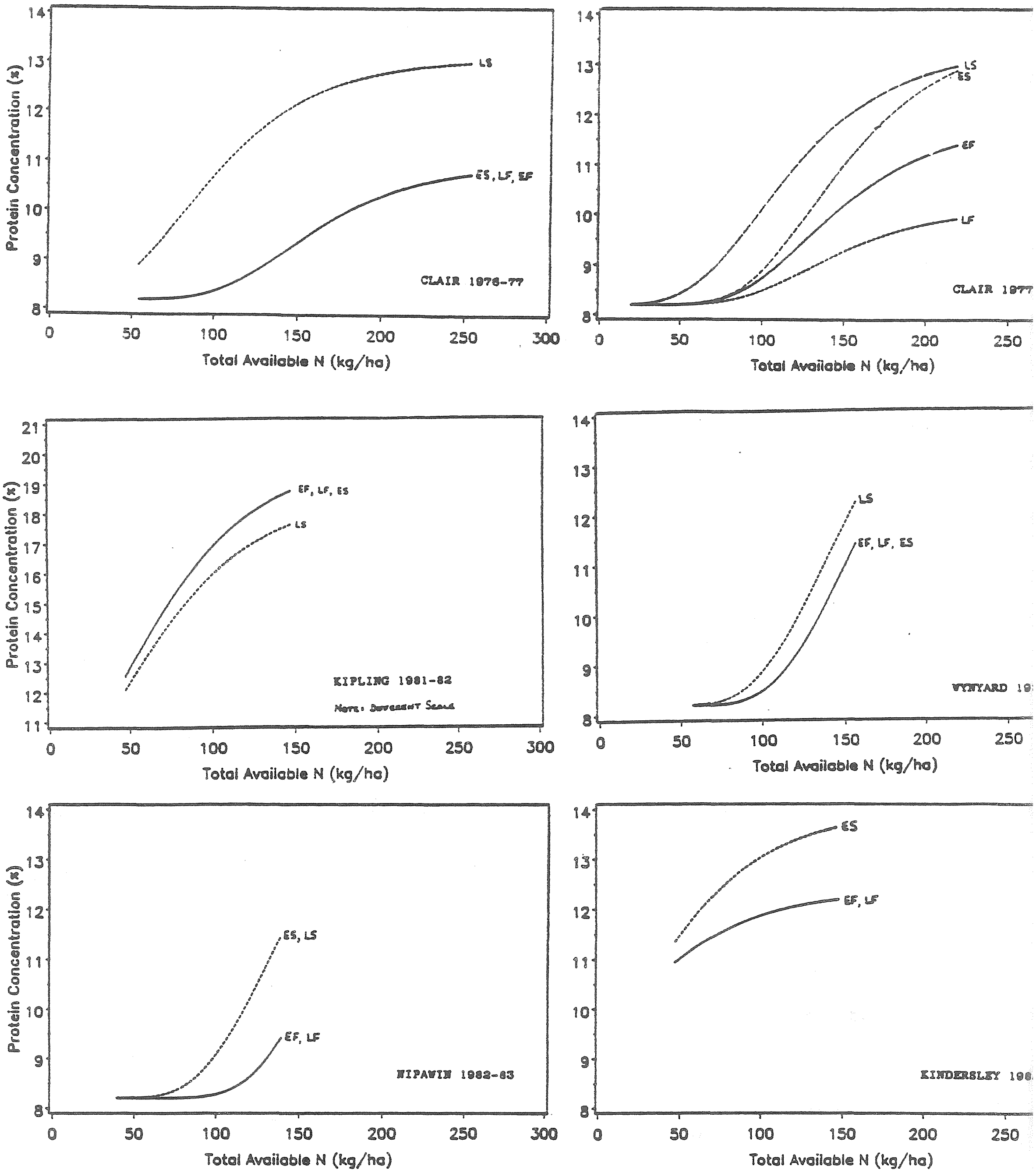


Figure 9. Grain protein concentration response to tota available N for locations where significant differences due to date of N application wer observed.

grain protein yield, and grain protein concentration. However, a deficiency in residual plant-available soil N and climatic factors favorable to plant growth and N response are prerequisites to the expression of these differences. While the stubbling-in production system usually results in low residual soil N levels, the semi-arid climate of this region often limits plant growth and N demand with the result that these prerequisites were not always met in the trials conducted in this study. However, when differences due to N application occurred, the following general response patterns were observed.

There is a minimum N level for plant growth that results in a constant ratio of total grain yield to grain protein yield and a minimum grain protein concentration (Terman et al., 1969). The minimum grain protein concentration observed in the present study was approximately 8.2%. Consequently, a lag phase is observed in the protein concentration N response curve when severe N stresses are corrected (Fig. 7 and 8). Once other environmental or genotypic factors become limiting to growth and subsequent increases in grain yield, excess N is shunted directly to grain protein production with the result that the protein concentration N response curve enters an increase phase. In certain years in the north-eastern part of the agricultural area of Saskatchewan (Clair 1976-77, 1977-78, 1982-83 and Nipawin 1982-83), losses of fall applied N were reflected in a shift of the grain and grain protein yield (Fig. 5 and 6) N response curves to the right and an increase in the lag phase or B value of the protein concentration N response curve (Fig. 9). For the remainder of the production region considered, N-use efficiency was as high, or higher, for fall compared to early spring applications.

Prolonged dry periods following spring applications resulted in fertilizer N being temporarily stranded at the soil surface thereby delaying its availability to the plant until after early spring N deficiencies had seriously limited the yield potential of the crop. Delays in spring N application had the same effect. Black and Siddoway (1977) have reported a similar significant influence of time of spring N application on grain yield response in Montana. In the rate and date study, delayed access meant that fertilizer N became surplus to the plant's minimum N requirements for growth at lower total N levels. This resulted in a more rapid increase in grain protein yield (Fig. 6) than total grain yield (Fig. 5), lower B values (Table 5) and a protein concentration N response curve that was shifted to the left (Fig. 9) as was observed for Clair 1976-77, 1977-78, Kindersley 1982-83 and Wynyard 1981-82.

Under average to good environmental conditions in Saskatchewan, the maximum N requirements of the winter wheat plant can be expected to have been met when the grain protein concentration N response curve reaches approximately 12.8% (Table 5). The protein concentration N response curve will reach a maximum near this level unless spring environmental conditions favorable for plant growth and N uptake are followed by extreme drought that severely limits grain yield, e.g., Kipling, Langbank, Carnduff 1981-82 and Meadow Lake 1982-83 (Fig. 8). Under these conditions fall and early spring N applications can often be expected to result in depressed grain yields (Fig. 5) and maximum protein concentrations ranging from 14.6 to 19.8% (Fig. 9).

From a practical standpoint, the results of this study demonstrate that date of broadcast N fertilizer application may have a significant influence on grain yield, grain protein yield and grain protein concentration of stubbled-in winter wheat produced in Saskatchewan. For maximum yield response and minimum N loss, broadcast N fertilizer should be applied as early as possible in the spring to increase the probability of subsequent rainfall moving the N into the rooting zone before the plants become N stressed (Black and Siddoway, 1977). Later N applications may have the effect of increasing grain protein concentrations at lower total N rates but this increase will normally occur as a result of decreased N use efficiency for grain yield. In the Brown and Dark Brown soil zones, where the risks of spring stranding are greatest and losses from denitrification are lowest, fall N applications for dryland stubbled-in winter wheat production may be a practical alternative to early spring N applications.

Method and Form

Significant ($P \leq 0.05$) grain yield responses to added fertilizer indicated that a N deficiency existed for seven of the nine test sites (Fig. 10). Grain yields ranged from a little more than one tonne ha^{-1} at Strasbourg to in excess of three tonne ha^{-1} at Clair in 1983-84. Grain yield response to added N were not detected at Saskatoon 1983-84 and Strasbourg 1984-85 where drought conditions were experienced.

The inverse polynomial function (Equation 1) also provided an excellent description of the grain and grain protein yield N fertilizer response observed in these trials (Fig. 10 and 11). The regression coefficients for the equations that best described grain yield and protein yield responses for each trial location are given in Tables 6 and 7. Predicted yields and protein yields from these equations accounted for 99.9 and 99.7% of the pooled variability in actual grain yield, respectively. A similarity of total grain yield and grain protein yield N response patterns observed in the present study once again demonstrated the closeness of the relationship between total grain yield and grain protein yield (Fig. 10 and 11).

The grain yield and protein yield N response curves (Fig. 10 and 11) for these trials demonstrate the large interaction between plant-available N and environmental conditions, especially moisture (Fowler et al., 1988a). Poor grain and protein yield N responses were observed for the dry locations, while larger N responses occurred under more favorable growing conditions (Fig. 10 and 11). The lack of grain and protein yield response to added N can be clearly seen for the Saskatoon 1983-84 and Strasbourg 1984-85 trials (Fig. 10 and 11).

The Gompertz equation (Equation 2) provided an excellent description of the relationship between grain protein concentration and total plant-available N for the trials in this study (Fig. 12). Predicted values from the grain protein concentration N response equations (Table 8) accounted for 99.0% of the pooled variability in actual protein concentration.

Again, the protein concentration N response curves for Clair 1982-83, 1983-84 and Watrous 1982-83 had extremely long lag phases (Table 8), and were the only locations that did not produce a significant ($P \geq 0.05$) increase in protein concentration for the range of N fertilizer considered (Fig. 12). Protein concentration N responses were observed for Saskatoon 1983-84 and Strasbourg 1984-85 although grain and grain protein yield N responses were not detected.

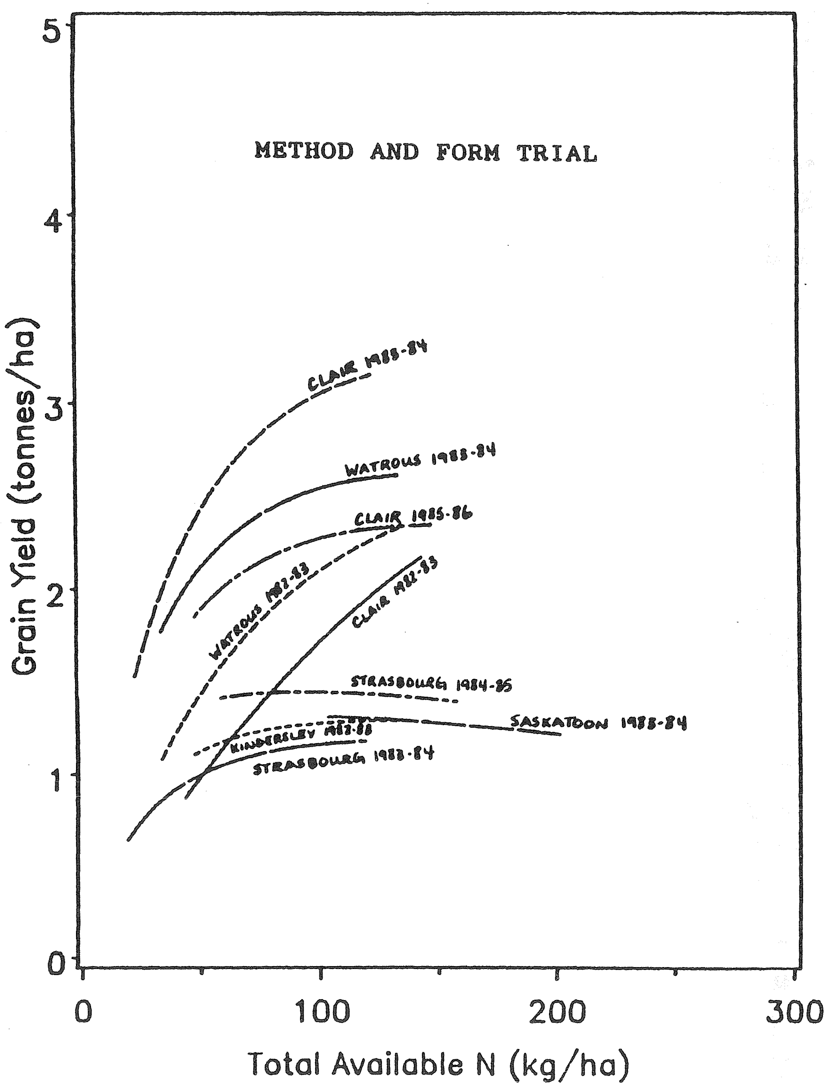


Figure 10. Grain yield response to total available N for method and form experiment.

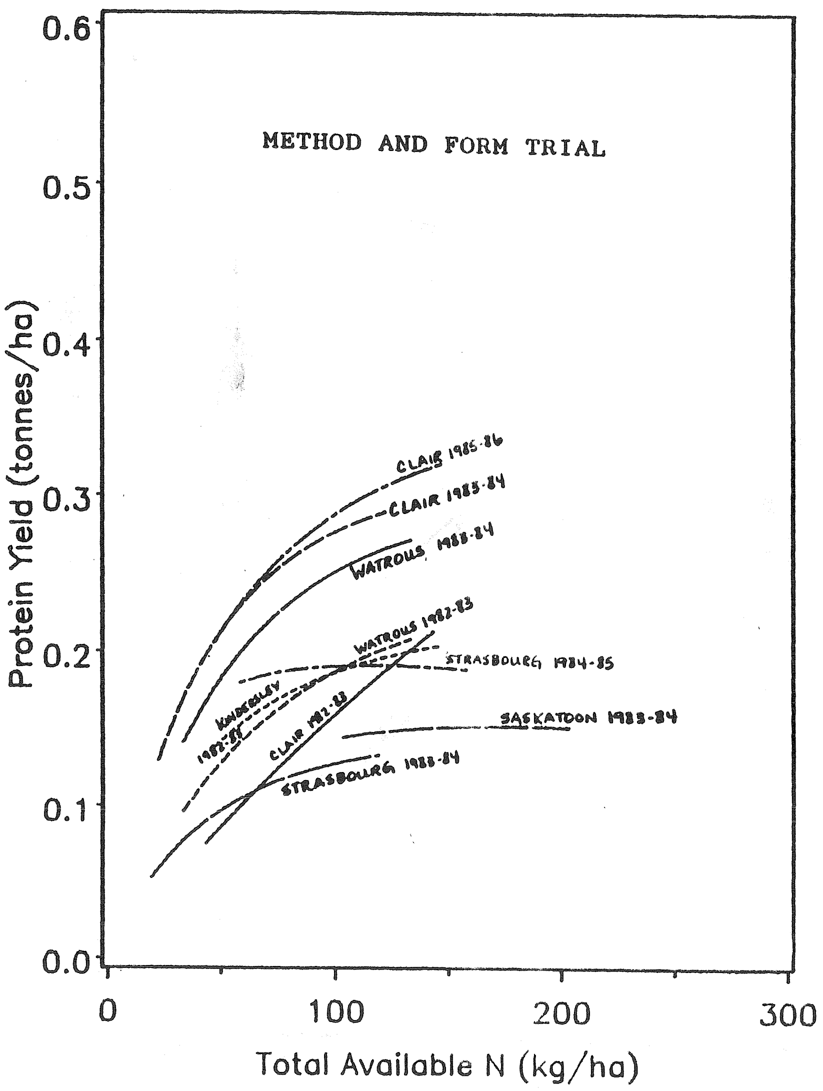


Figure 11. Grain protein yield response to total available N for method and form experiment.

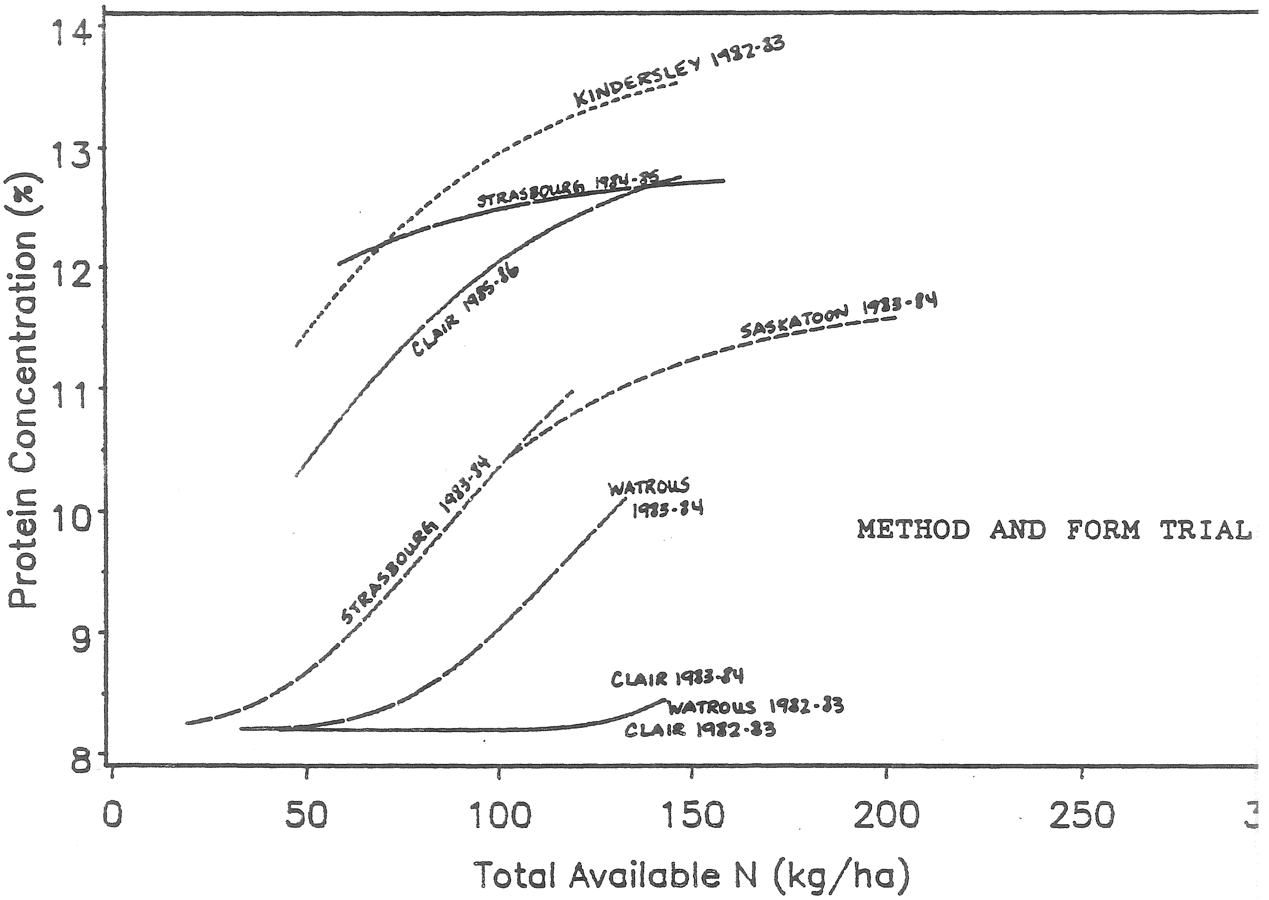


Figure 12. Grain protein concentration response to total avai able N for method and form experiment.

Early fall banding of urea and ammonium nitrate gave similar grain and protein yield N responses for all locations in the method and form study (Table 6 and 7). With the exception of Kindersley 1982-83, early spring broadcast ammonium nitrate also gave similar results to early fall banding treatments (Fig. 13 and 14). The absence of significant rainfall from the time of N application (Table 2) until 18 June meant that the spring broadcast fertilizer N (urea and ammonium nitrate) was positionally unavailable until after N deficiencies had limited grain yield potential at Kindersley 1982-83 (Fig. 13). Grain protein yield response to added N (Fig. 14) was not limited to the same extent and, as a result, grain protein concentration (Fig. 15) was higher for the spring applications at this location. The surface stranding of spring applied fertilizer produced similar crop responses for both urea and ammonium nitrate. The importance of applying broadcast N fertilizer at the earliest opportunity in the spring was again emphasized at Kindersley 1982-83. At this location, there was ample opportunity to broadcast N on dry fields in early April before a heavy snowfall that would have provided adequate surface moisture to move the N into the crop rooting zone prior to the onset of the spring drought.

Significant ($P \leq 0.05$) total grain (Fig. 13) and grain protein (Fig. 14) yield reductions were observed for late fall urea and ammonium nitrate and early spring urea broadcast applications at Clair 1982-83, and early fall urea broadcast applications at Watrous 1982-83 and Clair 1983-84 (Table 1). These are the same three trials that did not produce measurable increases in protein concentration for the range of N fertilizer considered. The spring of 1982-83 was particularly cool and damp until the end of May at both Clair and Watrous. Similar spring conditions were experienced at Clair in 1983-84 where snow and cool damp weather in early May resulted in a delay in the seeding of spring crops. The long lag phase of the grain protein concentration N response curves for these locations (Fig. 12) suggest that there may have been significant N losses for all fertilizer treatments considered. A horizontal "lag" or shift in total grain (Fig. 13) and grain protein (Fig. 14) yield N response curves to the right also reflected the reduced N-use efficiency, probably due to denitrification losses (Malhi and Nyborg, 1983) for late fall broadcast urea and ammonium nitrate. As a practical example of the magnitude of these losses, 100 kg N ha^{-1} applied in the late fall produced grain (grain protein) yields that were equal to those from 82(77) kg N ha^{-1} applied for ammonium nitrate broadcast in the early spring. Similar directional shifts in the total grain (Fig. 13) and grain protein (Fig. 14) yield N response curves also identified N losses for broadcast urea applied in early spring at Clair 1982-83 and early fall at Watrous 1982-83, and Clair 1983-84. The absence of yield reductions for similar ammonium nitrate treatments suggest losses with urea were due to volatilization. In these instances, 100 kg N ha^{-1} applied as urea in the early spring at Clair 1982-83 and early fall at Watrous 1982-83 and Clair 1983-84, produced grain (grain protein) yields that were equal to those produced by 82(77), 66(74), and 58(46) kg N ha^{-1} applied as ammonium nitrate broadcast at the same times, respectively. These observations once again demonstrate that the potential N losses associated with broadcast applications of urea in surface residues can be quite large (Kresge and Satchell, 1960; Carter and Rennie, 1984; Keller and Mengel, 1986; McInnes et al., 1986). However, when compared to ammonium nitrate, significant yield losses with urea were only observed for three of nine trials in this study suggesting that, on average, actual losses with urea were not a major problem. These observations emphasize the major difficulty with urea. This

Table 6. Estimated regression coefficients for grain yield in Equation 1 for method and form trials.

Location[†]	Nitrogen treatment[‡]	u	e	s
1	LF urea+AN, ES urea	10459	19.9	903
	Remaining treatments	11862	23.1	903
2	EF,LF urea + AN	4293	40.6	601
	ES (AN+urea)	1816	70.0	903
3	EF broadcast urea	3017	52.1	903
	Remaining treatments	5194	43.3	903
4	EF-BC urea	3986	106.5	903
	Remaining treatments	5143	102.6	903
5	All treatments	1661	137.8	903
6	All	1715	55.7	903
7	All	3920	105.0	903
8	All	1822	154.9	903
9	All	3523	93.3	903

[†] See Table 2 for actual locations.

[‡] EF-early fall, LF-late fall, ES-early spring, AN-ammonium nitrate

Table 7. Estimated regression coefficients for grain protein yield in Equation 1 for method and form trials.

Location[†]	Nitrogen[‡] Treatment	u	e	s
1	LF urea and AN, ES urea	471	2.05	949
	Remaining treatments	3980	1.87	949
2	Remaining treatments	524	4.43	949
	ES urea and AN	304	5.67	949
3	EF broadcast urea	278	5.11	949
	Remaining treatments	458	3.85	949
4	EF broadcast urea	297	9.74	949
	Remaining treatments	496	8.23	949
5	All treatments	239	4.92	949
6	All treatments	235	3.65	949
7	All treatments	512	6.21	949
8	All treatments	253	13.62	949
9	All treatments	500	7.78	1851

[†] See Table 2 for actual locations.

[‡] EF-early fall, LF-late fall, ES-early spring, AN-ammonium nitrate.

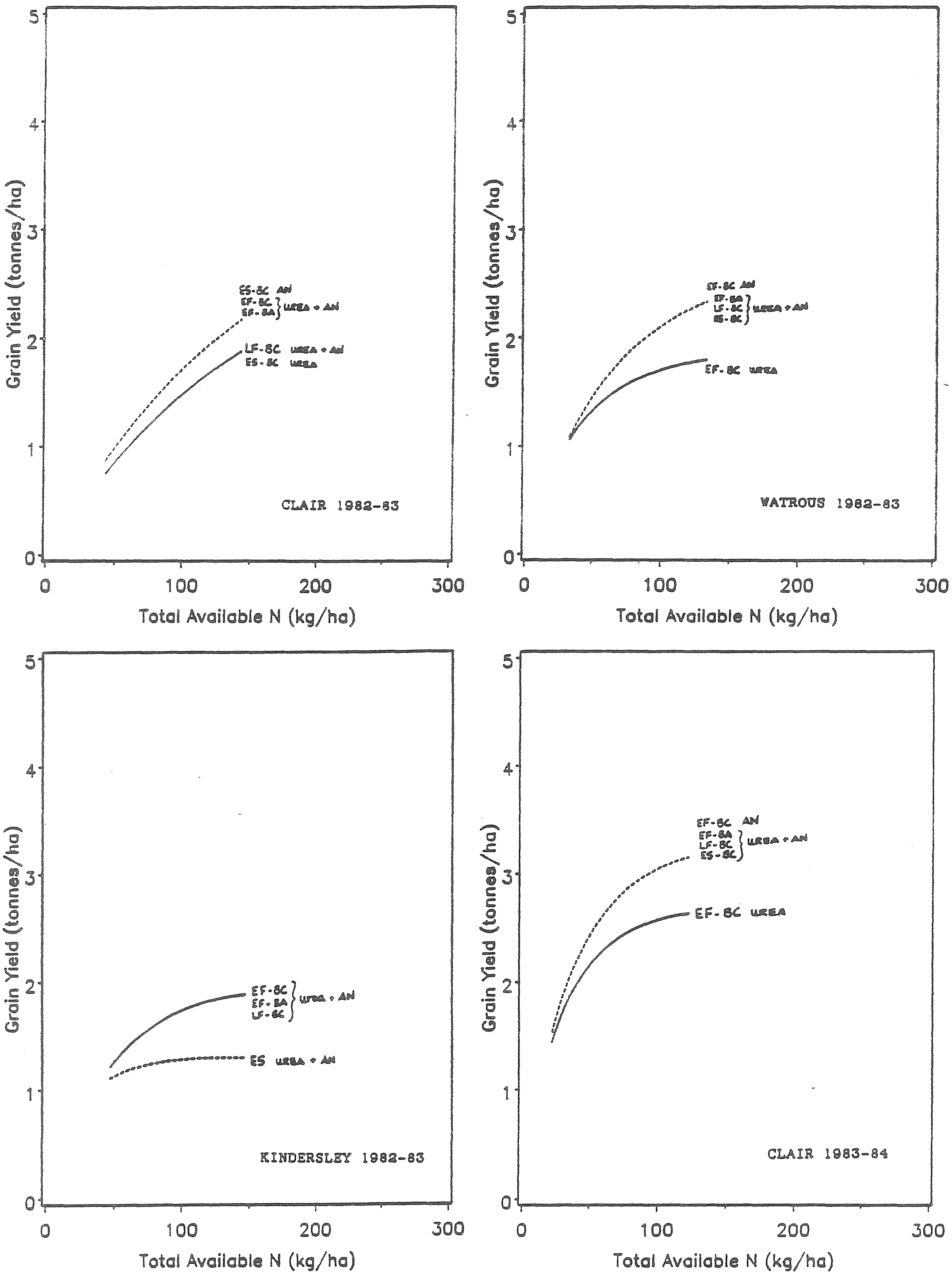


Figure 13. Grain yield response to total available N for locations where significant differences due to N formulation and method of application were observed.

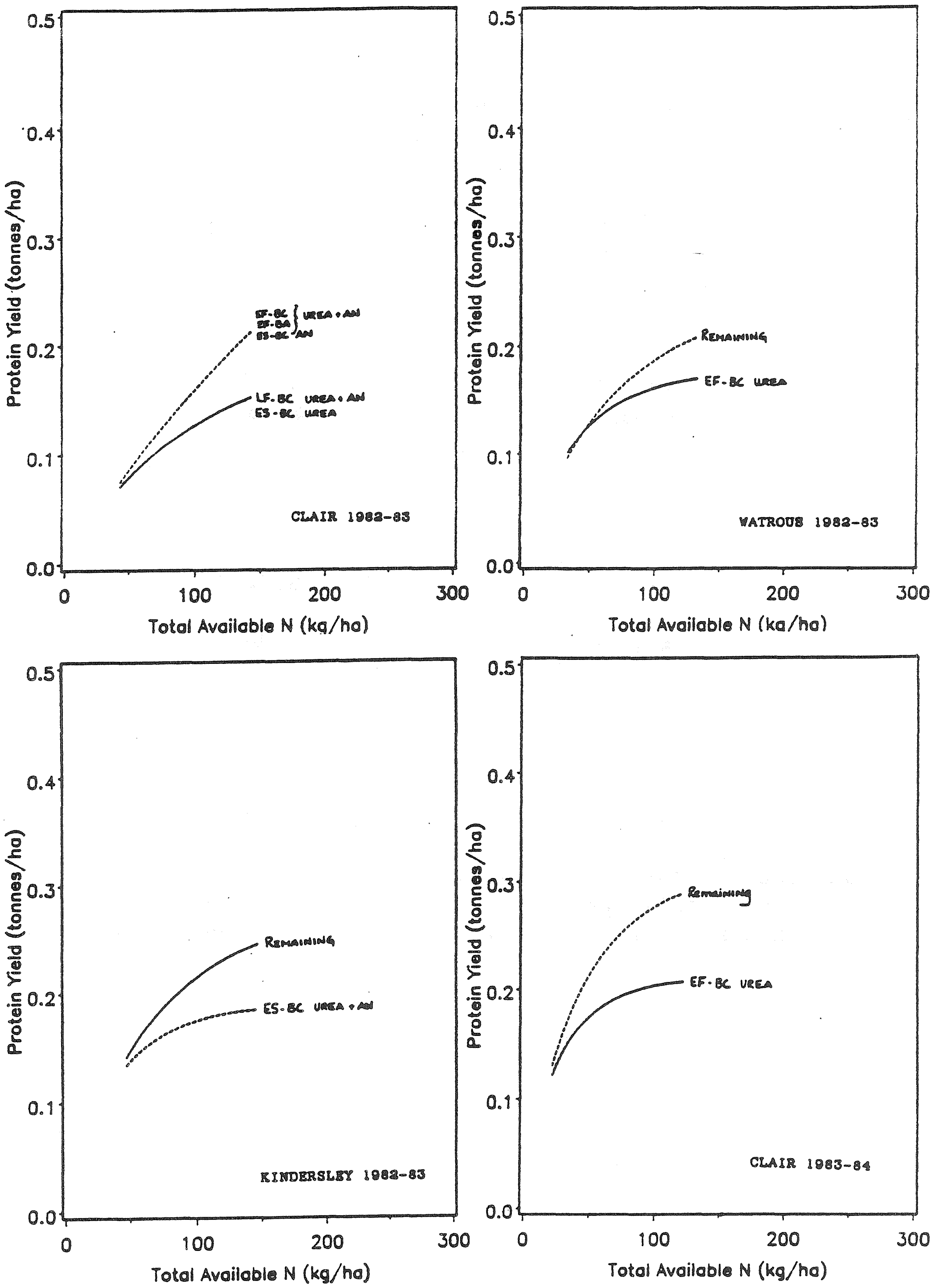


Figure 14. Grain protein yield response to total available N for locations where significant differences due to N formulation and method of application were observed.

Table 8. Estimated regression coefficients for grain protein concentration in Equation 2 for method and form trials.

Location[†]	Nitrogen[‡] Treatment	A[††]	B
1	All	N/A	>70
2	ES urea and AN	5.66	1.73
	Remaining treatments	3.93	1.22
3	All	N/A	>70
4	All	N/A	>70
5	All	3.54	4.80
6	All	4.36	6.98
7	All	3.93	15.46
8	All	4.61	0.71
9	All	4.97	2.56

[†] See Table 2 for actual locations.

[‡] EF - early fall, LF - late fall, ES - early spring, AN - ammonium nitrate.

[††] NA - Maximum N rates applied were not high enough to provide an estimate of A.

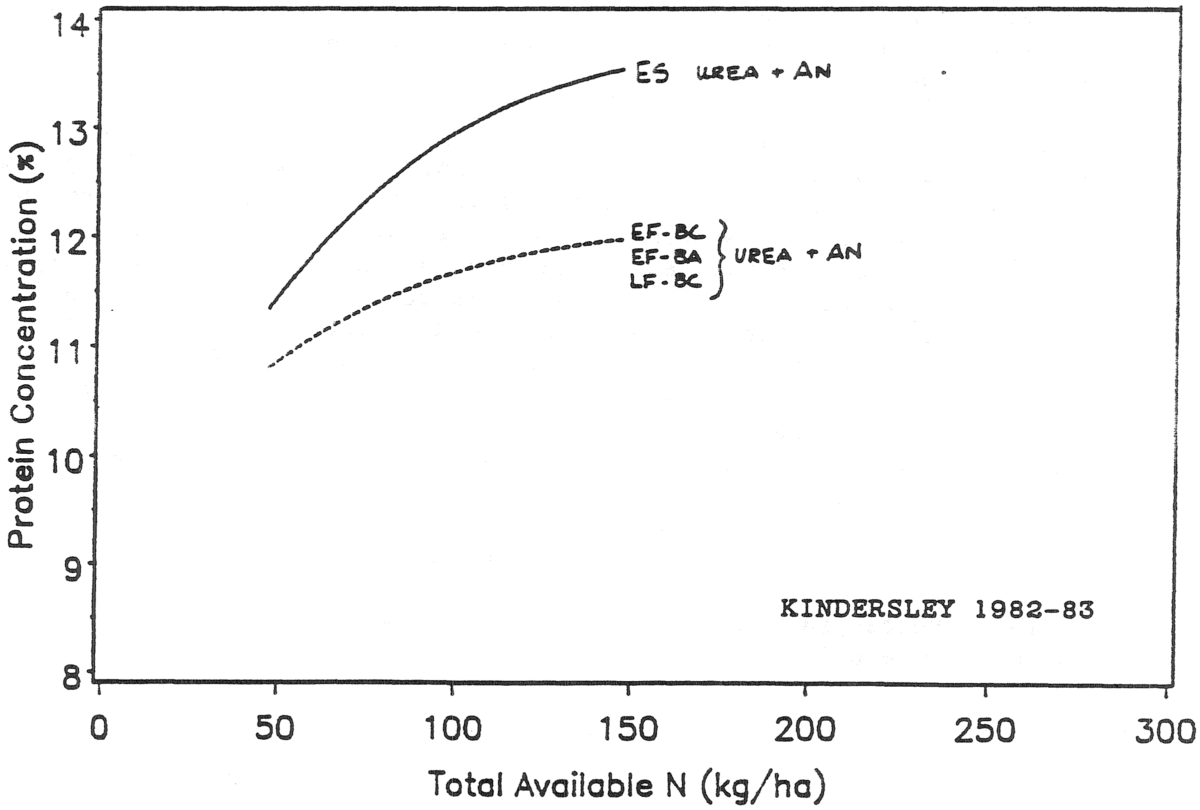


Figure 15. Grain protein concentration response to total available N for locations where significant differences due to N formulation and method of application were observed.

is that specific environmental conditions are required for volatilization losses to occur making the potential for losses as unpredictable as the weather. For this reason, potential losses with broadcast urea cannot be corrected for by simply increasing application rates to compensate for average losses.

Fall banding was effective in reducing losses with urea but, as mentioned earlier, the problems of equipment availability, time and seedbed damage must be dealt with. Ammonium nitrate broadcast at the same time as the banding treatments were made, performed as well as both banded urea and ammonium nitrate. However, it has been demonstrated that in some years losses from early fall broadcast ammonium nitrate can be quite large, especially in the Black and Grey soil zones (Fowler and Brydon, 1988). Unfortunately, the weather conditions that lead to losses of N from early fall broadcast ammonium nitrate (as seen from the rate and date study) were not encountered in these trials. Therefore, the question of potential losses from early fall banding of both urea and ammonium nitrate have not been completely answered by the method and form study.

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