In-crop application effect of nitrogen fertilizer on grain protein concentration of spring wheat in the Canadian prairies

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[1]*Crop Diversification Division, Alberta Agriculture, Food and Rural Development, Lethbridge, Alberta, Canada T1J 4V6 (e-mail: ross.mckenzie@gov.ab.ca) ;* [2]*Symbio Ag Consulting, Lethbridge, Alberta, Canada T1K 2B5;* [3]*Agriculture and Agri-Food Canada, Box 1000A, Brandon, Manitoba, Canada R7A 5Y3;* [4]*Phosphate and Potash Institute of Canada, Suite 704, CN Tower, Midtown Plaza, Saskatoon, Saskatchewan, Canada S7K 1J5;* [5]*Crop Diversification Division, Alberta Agriculture, Food and Rural Development, Edmonton, Alberta, Canada T6H 4P2.* *Received 29 March 2005, accepted 21 November 2005.*

McKenzie, R. H., Bremer, E., Grant, C. A., Johnston, A. M., DeMulder, J. and Middleton, A. B. 2006. **In-crop application effect of nitrogen fertilizer on grain protein concentration of spring wheat in the Canadian prairies.** Can. J. Soil Sci. **86**: 565–572. Due to the price premium for high-protein wheat (*Triticum aestivum* L.), many producers are interested in the efficacy of in-crop application of low rates of N fertilizer for increasing grain protein concentration (GPC). We conducted field studies at 26 site-years in Alberta, Saskatchewan and Manitoba from 1998 to 2000 to determine if in-crop application (tillering, boot stage or anthesis) of N fertilizer [broadcast ammonium nitrate (AN) or foliar urea-ammonium-nitrate solution (UAN); 15 kg N ha^{-1}] could economically increase GPC of a Canada Western Red Spring (CWRS) wheat cultivar (AC Barrie). Basal N fertilizer rates were 60 and 120 kg N ha^{-1}. The average increase in GPC due to in-crop N application was 3 g kg^{-1}. The increase in GPC was similar at basal N rates of 60 and 120 kg N ha^{-1}. Broadcast AN and foliar-applied UAN were generally equally effective at increasing GPC, but were not more effective than application at the time of seeding. Late application tended to increase GPC more effectively than early application. The increase in GPC due to application of in-crop N was not economic at most sites in this study, but might be greater if applied under more N deficient conditions.

Key words: Split N application, foliar, timing

McKenzie, R. H., Bremer, E., Grant, C. A., Johnston, A. M., DeMulder, J. et Middleton, A. B. 2006. **Incidence d'une application d'engrais azoté pendant la croissance sur la concentration de protéines dans le grain du blé de printemps des Prairies canadiennes**. Can. J. Soil Sci. **86**: 565–572. À cause du prix plus élevé du blé (*Triticum aestivum* L.) à forte teneur en protéines, bon nombre de cultivateurs s'interrogent sur l'efficacité d'une légère application d'engrais azoté pendant la croissance, en vue de relever la concentration de protéines dans le grain (CPG). De 1998 à 2000, les auteurs ont procédé à des études sur le terrain à 26 sites-année en Alberta, en Saskatchewan et au Manitoba en vue d'établir si l'application d'engrais N (épandage à la volée de nitrate d'ammonium [NA] ou application foliaire d'une solution d'urée et de nitrate d'ammonium [UNA] à raison de 15 kg de N par hectare) pendant la croissance (au tallage, à la fin de la montaison ou à l'anthèse) permettrait d'accroître économiquement la CPG d'un cultivar (AC Barrie) de blé roux de printemps de l'Ouest canadien. Les taux d'application de base étaient de 60 et 120 kg de N par hectare. L'application d'engrais azoté pendant la croissance entraîne une hausse moyenne de 3 g par kg de la CPG. Cette hausse est similaire pour les deux taux d'application. En général, l'épandage de NA à la volée et l'application foliaire de UNA augmentent la CPG avec la même efficacité, mais cette efficacité ne dépasse pas celle d'une application lors des semis. Une application tardive a tendance à augmenter plus efficacement la CPG qu'une application hâtive. La hausse de la CPG attribuable à l'application d'un engrais N à la culture n'est pas suffisante pour être rentable à la majorité des endroits étudiés, mais elle pourrait être plus importante aux endroits plus carencés en N.

Mots clés: Application fractionnée de N, foliaire, choix du moment

An acceptable range of grain protein concentration for bread-making with CWRS wheat is 120 to 135 g kg^{-1}, although higher GPC may be necessary for certain specialty breads or for blending with wheat having low GPC (Canadian Wheat Board 2004). As GPC increases from 110 to 150 g kg^{-1}, wheat growers receive an incremental price premium that varies from year to year, depending on market conditions.

Grain protein concentration is generally unaffected or declines with the first increment of N fertilizer addition under extremely N deficient conditions, but increases rapidly as N availability approaches the amount required for maximum grain yield, with maximum GPC generally achieved at levels of N availability much higher than that required for maximum yield (Fig. 1) (Terman et al. 1969;

Abbreviations: AN, ammonium nitrate; **ANR**, available N ratio; **CWRS**, Canada Western Red Spring; **GPC**, grain protein concentration; **UAN,** urea-ammonium-nitrate

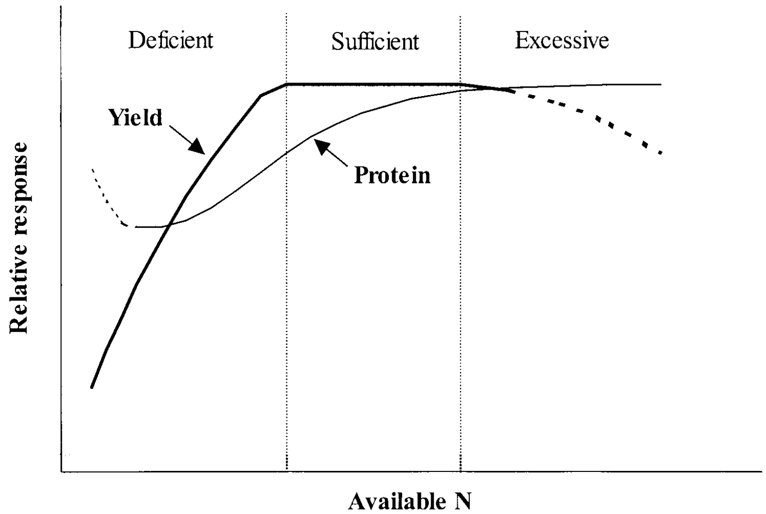

Fig. 1. Typical response of grain yield and protein concentration to available N.

Campbell et al. 1997; Fowler 2003). Due to uncertainty in potential grain yield, growers may desire to only apply sufficient fertilizer N for average yields at planting and then ensure adequate GPC by applying additional N at a later date if weather conditions are favourable. In-crop application of N may also be more effective for increasing GPC than pre-seeding application (Gooding and Davies 1992; Wuest and Cassman 1992).

Nitrogen fertilizer can be applied to a growing wheat crop by broadcast application of granular fertilizer [e.g., ammonium nitrate (AN)] or by foliar or surface dribble-banded application of liquid fertilizer [e.g., urea or urea-ammonium-nitrate (UAN) solutions]. Split application of granular N fertilizer is frequently used to improve N use efficiency and grain protein, particularly under irrigation (e.g., Carefoot et al. 1993). Under dryland conditions, late application of granular fertilizer may be ineffective if rainfall is insufficient to move applied N into the root zone. Foliar application of urea or UAN has been tested in a number of research trials. In Kansas, a single spray of urea at flowering, the most effective stage, increased GPC of a hard red winter wheat by 2.5, 7.5 and 44 g kg^{-1} when applied at rates of 11, 34 and 56 kg N ha^{-1}, respectively (Finney et al. 1957). In a 2-yr field study conducted in Manitoba, foliar-applied urea or broadcast AN applied 10 or 11 wk after seeding at 34 kg N ha^{-1} increased GPC of a hard red spring wheat in a year with high grain yields, but not in a year with low grain yields (Alkier et al. 1972). In a 3-yr field study conducted at two locations in Oklahoma with hard red winter wheat, foliar application of UAN at 34 kg N ha^{-1} at Feekes 10.5 (pre-flowering) and Feekes 10.5.4 (post-flowering) stages increased GPC over that of the check (no foliar N applied) by 15 and 14 g kg^{-1}, respectively (Woodfolk et al. 2002). In a 6-yr field study conducted in South Dakota, foliar application of UAN at 34 kg N ha^{-1} at the boot stage significantly reduced grain yield of hard red spring wheat by 5%, but did not affect grain yield of hard red winter wheat (Bly and Woodard 2003). Grain protein concentration was increased more when UAN was applied post-pollination than at the boot stage. Post-pollination foliar UAN application increased protein 70% of the time when the yield goal was exceeded, compared with only 23% when it was not. Negative effects of foliar urea application on plant productivity may occur due to desiccation of leaf cells, aqueous ammonia and urea toxicity, biuret contamination, and/or the disruption of carbohydrate metabolism (Gooding and Davies 1992).

Our objective was to determine if in-crop application (tillering, boot stage or anthesis) of N fertilizer [broadcast ammonium nitrate (AN) or foliar urea-ammonium-nitrate (UAN); 15 kg N ha^{-1}] could economically increase GPC of a CWRS wheat cultivar.

MATERIALS AND METHODS

Field experiments were conducted at 26 site-years (sites) from 1997 to 2000: 11 in southern Alberta, 8 in central Alberta, 2 in northeastern Saskatchewan (Melfort) and 5 in southern Manitoba (Brandon) (Table 1). Three sites in southern Alberta were irrigated (Lethbridge); all other sites were rainfed. Most sites were located on commercial fields, and all sites were located on cereal or canola stubble. Except for irrigated and Manitoba sites, minimum tillage practices had been in use for at least 5 yr.

At each site, an experiment was set up with 17 treatments arranged in a randomized complete block design with four blocks. Urea was banded at seeding at 0, 60, 75, 120 and 135 kg N ha^{-1}. At urea application rates of 60 and 120 kg N ha^{-1}, N was also applied at 15 kg N ha^{-1} at tillering, boot stage and anthesis by broadcast application of AN and foliar application of UAN. The 15 kg N ha^{-1} rate was selected to avoid possible leaf burn from foliar UAN applications and to reflect typical recommendations. Broadcast AN was applied with a fertilizer spreader at tillering and by hand at later application dates. Foliar-applied UAN was applied

Table 1. Site characteristics

Site no.	Location	Great group[z]	Year	Precipitation (mm) May	June	July	Aug.	Sum	Soil pH 0– 0.15 m	NO_3-N 0–0.6 m (kg ha^{-1})
Southern Alberta, irrigated										
1	Lethbridge	Dark Brown	1998	55	241	26	33	356	7.7	77
2	Lethbridge	Dark Brown	1999	31	128	174	70	404	7.6	89
3	Lethbridge	Dark Brown	2000	52	161	110	21	344	7.6	27
Southern Alberta										
4	Bow Island	Brown	1998	57	121	38	12	228 (126)	6.7	4
5	Welling	Dark Brown	1998	57	122	34	12	226 (108)	7.1	13
6	Bow Island	Brown	1999	49	75	32	43	199 (109)	6.6	12
7	Lethbridge	Dark Brown	1999	51	67	57	38	213 (74)	6.1	43
8	High River	Black	1999	60	111	141	81	393 (187)	6.9	37
9	Bow Island	Brown	2000	10	61	7	8	86 (47)	6.0	13
10	Lethbridge	Dark Brown	2000	10	38	11	6	65 (31)	6.0	19
11	High River	Black	2000	5	53	5	40	103 (36)	6.9	41
Central Alberta										
12	Vegreville	Black	1998	16	109	36	30	191 (74)	Not determined	
13	Devon	Black	1998	29	163	39	71	301 (100)	5.8	24
14	Barrhead	Gray	1998	28	59	59	19	165 (54)	5.5	59
15	Vegreville	Black	1999	37	17	72	68	194 (75)	5.6	88
16	Leduc	Black	1999	96	39	107	56	297 (98)	6.4	40
17	Barrhead	Gray	1999	35	66	50	40	191 (63)	6.2	42
18	Ryley	Black	2000	33	66	106	43	248 (95)	5.5	40
19	Leduc	Black	2000	61	92	116	31	300 (99)	7.4	57
Saskatchewan										
20	Melfort	Black	1998	33	88	43	6	170 (70)	7.1	35
21	Melfort	Black	1999	44	75	96	37	253 (104)	7.6	28
Manitoba										
22	Brandon	Black	1997	11	43	103	35	192 (73)	7.3	77
23	Brandon	Black	1998	78	193	107	144	522 (198)	7.4	41
24	Brandon	Black	1998	84	170	78	123	455 (172)	8.0	38
25	Brandon	Black	1999	188	58	99	108	452 (171)	7.2	85
26	Brandon	Black	1999	207	57	105	61	430 (163)	7.8	84

[z]All soils are Chernozemic except Gray soils, which are Luvisolic.
[y]Values in parentheses are percentages of long-term average precipitation at the nearest meteorological station for the months of May through July. Irrigation is included in precipitation.

with a small plot sprayer using commercially available UAN (28-0-0) that was diluted by 50% with water.

Soil samples were obtained in fall (dryland sites in southern Alberta, Saskatchewan and Manitoba sites) or early spring. Soil samples consisted of 20 small cores (2 cm) from the whole site area at central Alberta sites, five large cores (5 cm) from each block at southern Alberta sites, eight large cores from each block at Saskatchewan sites, and two large cores from each block at Manitoba sites. Samples were obtained at depths of 0-15, 15-30 and 30-60 cm at all sites. All samples were air-dried and analyzed using standard soil testing methods. Precipitation was determined with rain gauges located on-site at all sites except those in central Alberta, where precipitation was obtained from the nearest Environment Canada meteorological station.

The wheat cultivar used at all sites was AC Barrie. Phosphorus fertilizer (triple superphosphate or monoammonium phosphate) was seed-placed at 13 kg P ha^{-1}. When required, K and S were also banded prior to seeding. The minimum plot size was 1.6 m by 8 m, while row spacing ranged from 0.2 to 0.22 m. Experiments were generally seeded in early to mid-May.

Plots were harvested with a small plot combine. Whole plots were harvested at the Alberta sites, while the centre five rows were harvested at the Saskatchewan and Manitoba sites. Grain protein concentrations were determined using near infrared spectroscopy (Foss NIRSystem Model #6500, Silver Spring, MD) or Kjeldahl analysis (O'Neill and Webb 1970; Technicon AutoAnalyzer II 1977), assuming a protein to N ratio of 5.7. All yields and concentrations are reported at 135 g moisture kg^{-1}.

Bartlett's test indicated that variances were not homogenous among sites, even when data were transformed, and thus pooled analyses were not conducted (Steel and Torrie 1980). Treatment effects were considered statistically significant at $P \leq 0.05$.

For treatments only receiving urea at planting, the significance of N rate effects on grain yield and GPC was determined with the Proc Mixed procedure of SAS (Release 8.01) (SAS Institute Inc., Cary, NC). Blocks were included as random effects and N rates were included as fixed effects. Treatment means were compared using the Tukey or Tukey-Kramer test. Planned *F* tests were conducted with the Proc Mixed procedure to determine the significance of the increase in GPC due to in-crop N application compared with basal N rate controls (60 and 120 kg N ha^{-1} applied at seeding) and same N rate controls (75 and 135 kg N ha^{-1} applied at seeding). Main effects and interactions of basal N rate, method of N application and time of N application were determined with the Proc Mixed procedure for increases in GPC relative to basal N rates (60 and 120 kg N ha^{-1}). Regression analysis was conducted using site means between the increase in GPC due to in-crop N application and the increase in GPC due to the same rate of additional N applied at seeding.

The net return for N applied at anthesis was calculated assuming no increase in grain yield, a protein premium of \$0.70 Mg^{-1} per 1 g kg^{-1} increase in GPC (average value for crop years 1999/2000 to 2003/2004, Canadian Wheat Board 2005), and a N cost of \$0.90 kg^{-1}.

RESULTS

Growing season precipitation ranged widely in this study, from 65 to 522 mm (Table 1). Sites in southern Alberta experienced very dry conditions in 2000, while those in Manitoba experienced very wet conditions in 1998 and 1999. Most sites received typical levels of growing season precipitation, from 160 to 300 mm.

Grain yields at 60 kg N ha^{-1} were not significantly less than maximum grain yields at all but two sites in this study (Table 2). Due to the sufficiency of 60 kg N ha^{-1} for maximum yield at most sites and the small increment of additional N, grain yields were unaffected when the N rate at seeding was increased from 60 to 75 kg N ha^{-1} or 120 to 135 kg N ha^{-1}.

Grain protein concentration at 60 kg N ha^{-1} was significantly less than maximum GPC at half of the sites in this study (Table 2). However, GPC was not affected at any site when the N rate at seeding was increased from 60 to 75 kg N ha^{-1} or 120 to 135 kg N ha^{-1}.

In-crop N application significantly increased GPC at 6 of 26 sites compared with basal N rates of 60 or 120 kg N ha^{-1} (Table 3). In-crop N application increased GPC at only one site compared with the same rates of N applied at seeding (75 and 135 kg N ha^{-1}). The average increase in GPC due to in-crop N application was 3.2 g kg^{-1} (range –3.0 to 13.0 g kg^{-1}) compared with basal N rates and 0.7 g kg^{-1} (range –2.8 to 5.2 g kg^{-1}) compared with the same rates of N applied at seeding.

Basal N rate, application method, application timing, or interactions affected the increase in GPC due to in-crop N application at all but two sites in this study (Table 3).

Interaction effects on the increase in GPC due to in-crop N application were seldom significant (Table 3). Two sites had a significant interaction of basal rate and application timing, but the responses were inconsistent. At site no. 6, the increase in GPC due to in-crop application was much greater at a basal rate of 120 kg N ha^{-1} than 60 kg N ha^{-1} when applied at anthesis, but similar at earlier application dates (data not presented). At site no. 14, the increase in GPC due to in-crop application was much greater at a basal rate of 60 kg N ha^{-1} than 120 kg N ha^{-1} when applied at tillering, but similar at later application dates (data not presented). Other interactions were either not significant at any site or were significant at a single site.

Basal N rate significantly affected the increase in GPC due to in-crop N application at 17 of 26 sites (Table 3). Of the sites where basal N effects were significant, 11 sites had a greater increase in GPC at 60 kg N ha^{-1} than at 120 kg N ha^{-1}, while six sites had a greater increase at 120 kg N ha^{-1} than at 60 kg N ha^{-1}. The average increase in GPC due to in-crop N application was similar at the two basal rates of N application (3.6 vs. 2.8 g kg^{-1}).

Application method significantly affected the increase in GPC due to in-crop N application at 4 of 26 sites (Table 3). Foliar-applied UAN had a greater increase in GPC than broadcast AN at three of these sites, while broadcast AN had a greater increase in GPC at the remaining site. The average increase in GPC due to in-crop N application was similar for the two application methods (3.4 vs. 3.1 g kg^{-1}).

Application timing significantly affected the increase in GPC due to in-crop N application at 8 of 26 sites (Table 3). At most sites with a significant effect of application timing, increases in GPC tended to increase with later date of application. The average increase in GPC due to in-crop N application was 2.3 g kg^{-1} when applied at tillering, 3.4 g kg^{-1} when applied at the boot stage, and 4.0 g kg^{-1} when applied at anthesis.

In general, a close relationship was observed between the increase in GPC due to in-crop application and the increase in GPC when additional N was applied at seeding (Fig. 2). One exception was a poor correlation when AN was broadcast at anthesis (Fig. 2f). This was likely due to the greater risk that N applied to the soil surface at anthesis was stranded at the soil surface and unavailable for crop uptake, as evidenced by lower than expected increases in GPC at a number of sites. Another exception was site no. 6, where application of N at tillering or boot stage was much more effective at increasing GPC than application at seeding or anthesis (Fig. 2). At this site, additional N applied at seeding was primarily used to increase grain yield and did not affect GPC (Table 2), while in-crop N applied increased both grain yield and GPC (data not presented). The ineffectiveness of additional N to increase GPC when applied at anthesis at this site may indicate that N was applied too late to be effectively utilized by the wheat crop.

Based on current prices, application of an additional 15 kg N ha^{-1} at anthesis only provided a positive economic return at 5 of 26 sites (assuming no increase in grain yield) (Table 3). On average, the cost of additional N was \$4 more than the increased value of the grain produced.

DISCUSSION

Many previous studies have shown that late in-crop application of N fertilizer is an effective method of increasing GPC. However, questions remain regarding the amount of increase that can be expected and the optimum method of application.

Table 2. Effect of N applied at seeding on grain yield and protein concentration of spring wheat at 26 sites on the Canadian prairies

	Grain yield (kg ha^{-1})						Grain protein concentration (g kg^{-1})					
Site no.	0	60	75	120	135	SE[y]	0	60	75	120	135	SE
1	3774b	4954a	4979a	5337a	5276a	204	157a	159a	158a	161a	161a	2.2
2	5231a	6207a	5356a	5668a	5892a	475	134a	151a	140a	148a	158a	6.9
3	2808c	3926b	3968ab	4254ab	4666a	160	108c	127b	130b	138ab	149a	3.1
4	775b	2552a	2865a	2681a	2872a	192	116b	103b	115b	144a	149a	4.8
5	1865c	3352ab	3278b	3597ab	4460a	186	109b	116b	117b	135a	142a	2.0
6	1404b	2275ab	2861a	3083a	2521a	179	116b	124b	120b	145ab	169a	7.7
7	3700b	4747a	4423a	4342a	4386a	118	131c	139bc	148ab	156a	157a	2.7
8	3724b	4307ab	4339ab	4615a	4450ab	184	117b	132a	128ab	132a	137a	2.6
9	685a	803a	1035a	961a	1058a	98	144b	175ab	175ab	182a	184a	7.9
10	1526b	1762ab	1807ab	1833a	1632ab	64	126c	154b	160ab	163ab	172a	3.1
11	3029a	3447a	3391a	3182a	3759a	198	112c	139b	143ab	157a	147ab	3.5
12	2444a	3013a	3012a	3133a	2919a	173	141a	144a	151a	157a	153a	5.3
13	2860b	3831ab	4161a	4424a	4511a	244	113c	132ab	127b	140ab	144a	3.5
14	3037a	3544a	3569a	3421a	3831a	189	128b	143a	147a	149a	152a	2.3
15	2476a	2919a	3242a	3126a	3248a	222	127b	151ab	152ab	152ab	160a	6.3
16	3924b	5064a	4824ab	5325a	5678a	234	114c	135b	135b	147a	149a	2.4
17	2763c	3891b	4182ab	4508a	4493ab	134	101c	116bc	131ab	143a	142a	3.5
18	3489b	4020ab	4320a	4179ab	4368a	184	124b	142ab	132ab	146a	144a	4.3
19	3180b	4487ab	4225ab	4807a	4664ab	225	113a	116a	120a	133a	127a	4.1
20	2028b	3874a	3692a	3458a	3536a	134	114c	126b	123b	153a	161a	1.9
21	3326b	4364a	4385a	4693a	4496a	187	117c	122bc	129bc	143a	148a	2.6
22	2696a	3019a	2634a	2668a	2725a	101	132a	137a	150a	152a	144a	7.2
23	3566a	3532a	3754a	3529a	3414a	163	150a	143a	147a	149a	152a	2.1
24	3625ab	3717a	3490ab	3288ab	3245b	98	138d	151c	154bc	160ab	162a	1.6
25	545b	1802ab	1295b	1952a	1918ab	161	126c	141b	137b	150a	150a	1.8
26	1937b	2639ab	2564b	2668ab	2728a	152	129a	127a	127a	134a	134a	2.1

[z]Values within the same row (site) followed by a common letter are not significantly different (Tukey or Tukey-Kramer test, $P = 0.05$).
[y]Standard error.

Increases in GPC due to in-crop application of N fertilizer in our study were small (average 3 g kg^{-1}, maximum 13 g kg^{-1}). In comparison, Finney et al. (1957) obtained an increase in GPC of hard red winter wheat of up to 44 g kg^{-1} with a single foliar application of urea at flowering. In-crop N application using broadcast AN or foliar-applied urea provided an average increase in GPC for hard red spring wheat (nonfallow) of 8 g kg^{-1} in a year with low yields and 26 g kg^{-1} in a year with high yields (Alkier et al. 1972). Woodfolk et al. (2002) obtained an increase in GPC of hard red winter wheat of 15 g kg^{-1} when UAN was foliar applied immediately after flowering.

One of the main factors responsible for the small increase in GPC due to in-crop N application in our study was the low rate of N application (15 kg N ha^{-1}). Finney et al. (1957) reported an increase in GPC of hard red winter wheat of 2.5 g kg^{-1} when urea was foliar applied at 11 kg N ha^{-1}, compared with an increase of 7.5 g kg^{-1} at 34 kg N ha^{-1} or 44 g kg^{-1} at 56 kg N ha^{-1}. Woodfolk et al. (2002) obtained an average increase in GPC of 5 g kg^{-1} when UAN was foliar applied at 11 kg N ha^{-1}, compared with an average increase of 15 g kg^{-1} at 34 kg N ha^{-1}.

The other factor responsible for the small increase in GPC due to in-crop N application in our study was the sufficiency of the lowest basal rate (60 kg N ha^{-1}) for maximum yield at most sites. Alkier et al. (1972) found a much larger increase in GPC due to in-crop N application in a year with high yields than in a year with low yields. Bly and Woodard (2003) found that postpollination foliar N increased GPC 70% of the time when the yield goal was exceeded, compared with only 23% when it was not. The average increase in GPC of hard red spring wheat due to foliar N application (34 kg N ha^{-1}) in their study was only 5 g kg^{-1}, which they largely attributed to lower than expected grain yields. High levels of available N reduce the benefit of in-crop N application by limiting the GPC response to further increases in available N (e.g., only 50% of sites in our study had a significant increase in GPC when N rates were increased from 60 to 135 kg N ha^{-1}) and by reducing the efficiency of N fertilizer use. Nitrogen fertilizer use efficiency declines rapidly as the rate of N fertilizer rates approaches or exceeds the amount of N required for maximum yield (e.g., G auer et al. 1992). In our study, increases in GPC due to N fertilizer application at anthesis accounted for only 16% of the N applied (based on data presented in Table 3).

The similar effectiveness of the three methods of applying an additional 15 kg N ha^{-1} (banded urea at seeding, broadcast AN and foliar UAN) was consistent with the results from some studies, but not others. In Manitoba, Alkier et al. (1972) found a similar increase in GPC of hard red spring wheat for broadcast AN and foliar-applied urea, but N applied during the growing season was more effective than N applied at seeding in a year with high yields. In Quebec, Bulman and Smith (1993) found that foliar-applied urea increased GPC of barley more effectively than broadcast AN in 2 of 4 yr and increased GPC more effectively than additional N applied at seeding in one of four years. Under irrigated conditions in California, broadcast application of AN at anthesis consistently improved GPC of a hard red spring wheat, with recovery of 55 to 80% of the N

Table 3. Effect of in-crop N application treatment on grain protein concentration and net return at 26 sites on the Canadian prairies

	Increase in grain protein concentration[z] (g kg^{-1})																			
	Compared with controls				Basal N rate[x] (B)			Application method (M)			Application timing[w] (T)				Interactions					Net return[u]
Site no.	Basal	N rate	Same	N rate	60 N	120 N	*P*	AN	UAN	*P*	Till	Boot	Anth	*P*	B × M	B × T	M × T	B × M × T	SE	($ ha^{-1})
1	0.5	NS[y]	0.9	NS	1.8	–0.9	**	0.6	0.3	NS	–1.8	1.0	2.2	**	NS	NS	NS	NS	1.4	–6
2	0.4	NS	1.1	NS	–6.7	7.6	***	1.3	–0.4	NS	0.1	–0.6	1.9	NS	NS	NS	NS	NS	4.7	–6
3	6.0	NS	–0.8	NS	1.3	10.8	***	9.4	2.7	*	5.6	6.4	6.1	NS	NS	NS	NS	NS	4.3	4
4	6.1	NS	–2.0	NS	12.1	0.2	***	4.5	7.9	NS	4.1	8.1	6.4	NS	NS	NS	NS	NS	4.3	–2
5	4.1	NS	0.1	NS	2.2	5.8	NS	3.8	4.2	NS	4.5	4.6	3.0	NS	NS	NS	NS	NS	3.0	–6
6	13.0	*	3.1	NS	10.1	16.0	NS	12.9	13.1	NS	10.9	17.0	11.2	NS	NS	*	NS	NS	6.9	6
7	4.6	NS	–0.6	NS	8.6	1.4	**	6.0	4.0	NS	2.0	3.9	9.0	*	NS	NS	NS	NS	3.6	15
8	3.1	NS	2.6	NS	–1.1	7.3	***	4.2	2.0	NS	2.2	3.5	3.6	NS	NS	NS	NS	NS	1.8	–3
9	0.2	NS	–0.6	NS	–2.1	2.7	*	0.4	0.2	NS	0.6	0.2	0.1	NS	NS	NS	*	NS	3.3	–13
10	7.4	**	0.0	NS	8.2	6.7	NS	7.5	7.3	NS	3.6	9.3	9.3	**	NS	NS	NS	NS	2.8	–1
11	–2.1	NS	0.5	NS	1.4	–5.6	**	–0.9	–3.4	NS	1.7	–4.3	–3.8	*	NS	NS	NS	NS	3.7	–23
12	3.9	NS	2.8	NS	10.1	–2.2	***	6.3	1.6	NS	3.7	4.6	3.5	NS	NS	NS	NS	NS	4.3	–6
13	0.3	NS	0.7	NS	–2.2	2.8	*	0.5	0.1	NS	–0.6	0.2	1.3	NS	NS	NS	NS	NS	3.5	–10
14	3.7	**	0.1	NS	5.1	2.4	**	2.5	4.9	**	3.0	4.4	3.8	NS	NS	*	NS	NS	1.4	–4
15	5.2	*	0.9	NS	2.4	8.0	***	4.6	5.8	NS	6.3	5.0	4.4	NS	NS	NS	NS	NS	2.5	–4
16	3.9	NS	2.9	NS	3.1	4.8	NS	3.3	4.5	NS	2.1	3.4	6.2	NS	NS	NS	NS	NS	2.7	9
17	4.6	NS	–2.1	NS	9.5	–0.2	***	4.0	5.3	NS	4.7	6.1	3.1	NS	NS	NS	NS	NS	4.5	–4
18	–3.0	NS	3.1	NS	–4.3	–1.7	NS	–3.3	–2.8	NS	–3.7	–5.4	0.1	*	NS	NS	NS	NS	2.8	–13
19	0.6	NS	2.0	NS	0.6	0.5	NS	–1.3	2.5	*	–1.5	1.0	2.3	NS	NS	NS	NS	NS	2.8	–7
20	–0.2	NS	–2.8	NS	1.3	–1.7	NS	–5.6	5.2	***	0.3	–4.3	3.5	*	NS	NS	NS	NS	3.7	–5
21	4.0	NS	–1.8	NS	6.9	1.2	**	4.2	3.9	NS	3.9	2.8	5.4	NS	NS	NS	NS	NS	2.8	3
22	5.5	NS	2.5	NS	9.5	1.6	NS	8.8	2.3	NS	–1.5	12.3	5.9	*	NS	NS	NS	NS	6.8	–2
23	3.4	*	–0.3	NS	5.4	1.4	**	4.0	2.7	NS	2.9	3.4	3.7	NS	NS	NS	NS	NS	1.9	–4
24	1.2	NS	–1.5	NS	2.9	–0.5	***	1.5	0.8	NS	–0.2	–0.2	4.0	***	NS	NS	NS	NS	1.5	–3
25	3.3	*	5.2	***	2.8	3.7	NS	3.0	3.5	NS	4.3	3.9	1.6	NS	NS	NS	NS	*	1.7	–12
26	3.6	NS	3.6	NS	5.3	1.8	*	4.9	2.3	NS	1.8	3.1	5.9	NS	NS	NS	NS	NS	2.6	–3
Minimum	–3.0		–2.8		–6.7	–5.6		–5.6	–3.4		–3.7	–5.4	–3.8						1.4	–23
Average	3.2		0.7		3.6	2.8		3.4	3.1		2.3	3.4	4.0						3.3	–4
Maximum	13.0		5.2		12.1	16.0		12.9	13.1		10.9	17.0	11.2						6.9	15

[z]Increase due to in-crop application of 15 kg N ha^{-1} compared with basal N controls (60 and 120 kg N ha^{-1} applied at seeding), except for comparison with same N rate controls (75 and 135 kg N ha^{-1} applied at seeding).
[y]NS, not significant.
[x]Application at basal N rates of 60 kg N ha^{-1} (60 N) and 120 kg N ha^{-1} (120 N).
[v]Application at tillering (Till), boot stage (Boot) and anthesis (Anth).
[u]Net return calculated for in-crop N applied at anthesis, assuming no increase in grain yield, protein premium of \$0.70 Mg^{-1} per 1 g kg^{-1} increase in GPC (based on crop years 1999/2000 to 2003/2004, Canadian Wheat Board 2005), and N cost of \$0.90 kg^{-1}.
*, **, *** $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively, based on planned *F*-test for comparisons to controls and analysis of variance for main effects and interactions.

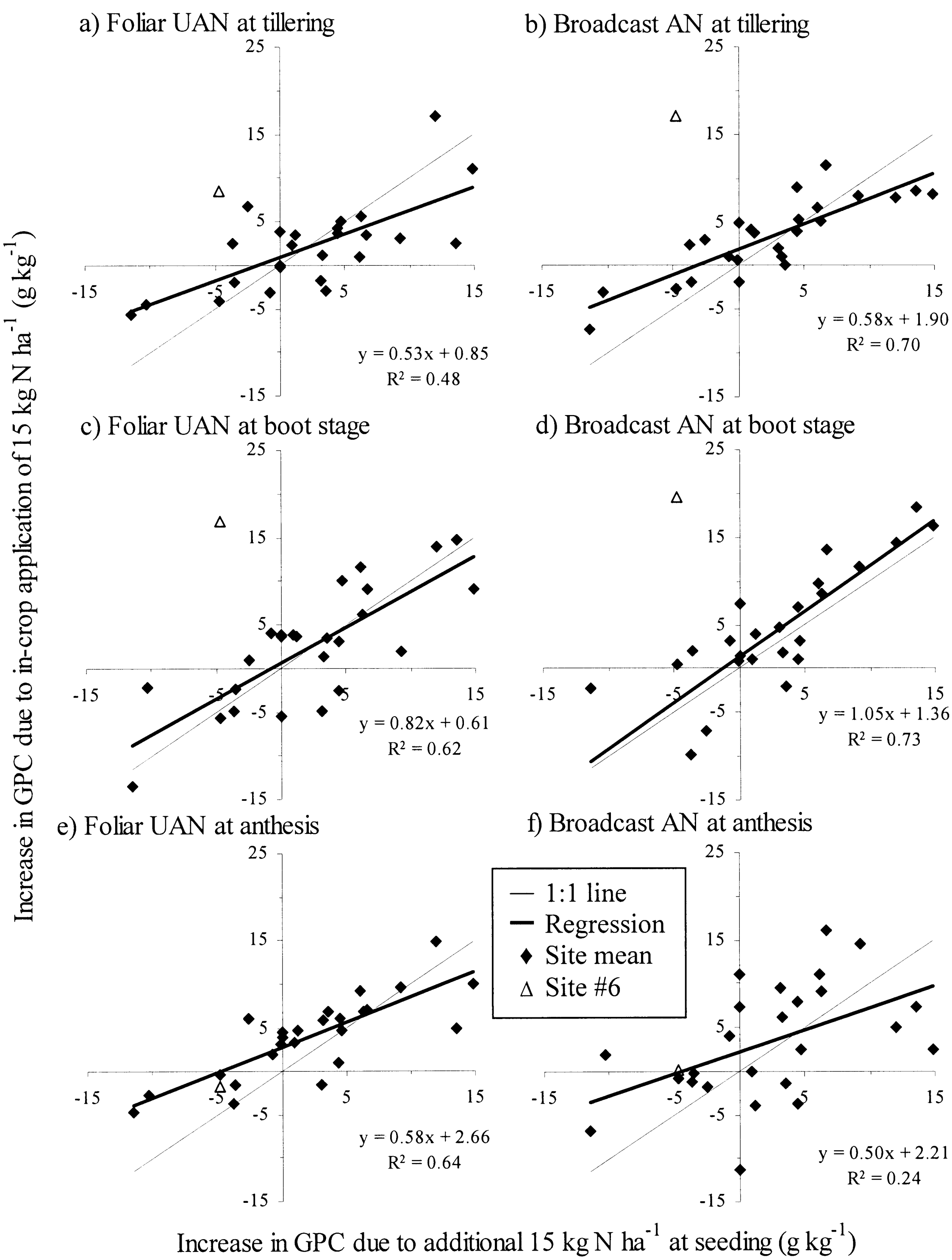

Fig. 2. Relationship between the increase in GPC due to in-crop N application and the increase in GPC due to the same amount of additional N applied at seeding (basal rate of 60 kg N ha^{-1}).

applied at anthesis, compared with recovery of 30 to 55% of N applied at seeding (based on recovery of ^{15}N-labelled AN) (Wuest and Cassman 1992). Recovery of ^{15}N-labelled AN was also increased when ^{15}N was applied at the boot stage, compared with application at seeding, in a 2-yr study conducted in Quebec (Tran and Tremblay 2000).

Differences in the effectiveness of N application methods to increase GPC depend on differences in N utilization (the proportion of acquired N used for grain protein synthesis) and N uptake efficiency. When available N is insufficient for maximum yield, then application of N at the time of seeding is primarily used to increase crop yields, and late application of N is a more effective method to increase GPC than early application (Terman et al. 1969; Palta and Fillery 1993; Fowler 2003). However, if available N is sufficient for maximum yield and losses of applied N are not affected by timing of N application, then additional N applied at seeding will be equally effective for increasing GPC as N applied at a later date. Effectiveness of N application method to increase GPC also depends on the efficiency of N uptake. For example, N fertilizer applied late in the growing season under dry conditions may be stranded near the soil surface and ineffective at increasing GPC. Direct absorption of foliar-applied N may circumvent this problem, but greenhouse studies with ^{15}N-labelled fertilizers indicate that most foliar-applied N must first be washed into the soil before it is taken up by wheat (Alkier et al. 1972; Rawluk et al. 2000). Conditions that favour losses of N early in the growing season reduce the effectiveness of N applied at seeding compared with N applied later. The similar effectiveness of the three methods of applying an additional 15 kg N ha^{-1} in our study indicates that N utilization and uptake efficiency were likely similar among methods. The similar effectiveness among methods of N application was also partly due to the low probability of detecting treatment differences at some sites with a limited GPC response to added N and high GPC variability.

The tendency for greater increases in GPC with later application of N in our study was consistent with previous studies (Finney et al. 1957; Wuest and Cassman 1992; Woodfolk et al. 2002). However, a minimal impact of timing at most sites can be attributed to the same reasons that N applied at seeding was often as effective at increasing GPC as in-crop N applications.

CONCLUSIONS

In-crop application of 15 kg N ha^{-1} did not economically increase GPC of CWRS wheat at most sites in this study. Increases in GPC were small due to the low rate of N addition and the general sufficiency of basal N rates for maximum grain yield. In general, broadcast AN and foliar-applied UAN were equally effective at increasing GPC, but were not more effective than application at the time of seeding. In-crop N application may be more effective if applied under more N deficient conditions.

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