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ARTICLE

Enhanced nitrogen management strategies for winter wheat production in the Canadian prairies

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Abstract: To address knowledge gaps around enhanced efficiency urea fertilizer efficacy for nitrogen (N) management, a study was designed to improve integrated nutrient management systems for western Canadian winter wheat producers. Three factors were included in Experiment 1: (*i*) urea type [urea, urea + urease inhibitor—Agrotain®; urea + urease and nitrification inhibitor—SuperU®, polymer-coated urea—Environmentally Smart Nitrogen® (ESN®), and urea ammonium nitrate (UAN)], (*ii*) application method (side-band vs. spring-broadcast vs. 50% side-band: 50% spring-broadcast), and (*iii*) cultivar (AC Radiant hard red winter wheat vs. CDC Ptarmigan soft white winter wheat). The Agrotain® and CDC Ptarmigan treatments were removed in Experiment 2 to allow for additional application methods: (*i*) fall side-band, (*ii*) 50% side-band — 50% late fall broadcast, (*iii*) 50% side-band — 50% early spring broadcast, (*iv*) 50% side-band — 50% mid-spring broadcast, and (*v*) 50% side-band — 50% late spring broadcast. CDC Ptarmigan produced superior grain yield and N utilization over AC Radiant. Grain yield and protein content were influenced by N form and application method. Split applications of N usually provided the maximum yield and protein, particularly with Agrotain® or SuperU®. Conversely, the UAN and ESN® forms, when all broadcast in spring, all side-banded in fall, or with late fall broadcasting, performed poorly. An exception to the poor fall-application results was the SuperU® treatments, which produced similar yield to the highest-yielding treatments. The results suggest that split applications of N might be most efficient for yield and protein optimization when combined with an enhanced efficiency urea product, particularly with urease or urease + nitrification inhibitors, and if the majority of N is applied in spring.

Key words: nitrogen, grain protein, Agrotain, SuperU®, ESN®, UAN®, nitrogen recovery.

Résumé : Pour enrichir nos connaissances sur les engrais à efficacité rehaussée comme l'urée dans le cadre de la gestion de l'azote (N), les auteurs ont conçu une étude qui devrait améliorer les systèmes de gestion intégrée des oligoéléments pour les producteurs de blé d'hiver de l'Ouest canadien. La première expérience portait sur trois paramètres : (*i*) le type d'urée (urée, urée + inhibiteur de l'uréase -Agrotain®; urée + inhibiteurs de l'uréase et de la nitrification – SuperU®, urée enrobée de polymère– ESN® et urée plus nitrate d'ammonium - UAN®), (*ii*) la méthode d'application (bandes latérales c. épandage à la volée au printemps c. 50 % bandes latérales et 50 % épandage à la volée au printemps) et (*iii*) le cultivar (blé d'hiver roux vitreux AC Radiant c. blé tendre blanc

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d'hiver CDC Ptarmigan). Les traitements Agrotain® et CDC Ptarmigan ont été supprimés lors de la deuxième expérience pour permettre l'intégration d'autres méthodes d'application, soit : (*i*) bandes latérales à l'automne, (*ii*) 50 % bandes latérales et 50 % épandage à la volée à la fin de l'automne, (*iii*) 50 % bandes latérales et 50 % épandage à la volée au début du printemps, (*iv*) 50 % bandes latérales et 50 % épandage à la volée au milieu du printemps, (*v*) 50 % bandes latérales et 50 % épandage à la volée à la fin du printemps. Le rendement grainier de CDC Ptarmigan dépasse celui d'AC Radiant, comme c'est le cas pour l'assimilation de l'azote par la plante. Le rendement grainier et la teneur en protéines subissent l'influence du type d'engrais N et de la méthode d'application. L'application fractionnée d'engrais N aboutit habituellement au rendement et à la concentration de protéines les plus élevés, surtout avec Agrotain® ou SuperU®. Inversement, les engrais UAN® et ESN® donnent de piètres résultats quand on les épand à la volée au printemps, en bandes latérales à l'automne ou à la volée à la fin de l'automne. L'engrais SuperU® est le seul à ne pas donner de piètres résultats quand on l'applique à l'automne, le rendement obtenu étant similaire à celui des traitements donnant le rendement le plus élevé. Ces résultats laissent croire que l'application fractionnée de N pourrait être le moyen le plus efficace d'optimiser le rendement et la concentration de protéines par l'usage d'urée à efficacité rehaussée, surtout avec un inhibiteur de l'uréase ou de l'uréase et de la nitrification, et lorsque la majeure partie du N est appliquée au printemps. [Traduit par la Rédaction]

Mots-clés : azote, teneur protéique du grain, Agrotain®, SuperU®, ESN®, UAN®, récupération de l'azote.

Introduction

Although marketing of small grains in western Canada is no longer a single desk monopoly governed by the Canadian Wheat Board, a minimum grain protein concentration of 115 g kg^{-1} (moisture basis of 135 g kg^{-1}) for Canada Western Red Winter Wheat (CWRW) was historically required for No. 1 and No. 2 CWRW. Recent work at Lacombe and Lethbridge, AB (Beres et al. 2010*a*, 2010*b*), and anecdotal reports from the industry, indicate that this standard can be difficult to meet; therefore, most grain buyers will accept 110 g kg^{-1} and blend to specifications accordingly in an effort to provide a consistent supply of winter wheat with this quality profile. Feed markets and the emergence of the ethanol feedstock market may negatively impact supplies of CWRW if producers perceive less risk and increased profitability in targeting starch production over protein production. Although genetic potential for grain protein accumulation is important, the expectation is that at least 110 g kg^{-1} of protein content can be achieved through appropriate nitrogen (N) management practices, provided a CWRW-eligible variety is selected. Therefore, it is essential that a sustainable N management package is adopted that optimizes protein performance and fully or partially integrates the latest innovations in N fertilizer.

The recommended timing, placement, and dose of N fertilizer vary widely for wheat production, but crop N demand is ultimately related to yield potential and water availability in rain-fed systems (Fowler et al. 1989*a*). The winter wheat growth habit presents unique challenges given the long duration of the vegetative growth stage and that the N needed during this phase to maintain the ideal leaf area to maximize photosynthetic activities is not easily synchronized with crop N demand compared with spring wheat. Thus, N requirements for winter wheat exceed spring wheat by 25%–50% in the prairies, generally reaching a peak along response curves between 135 and 170 kg N ha^{-1} (Fowler et al. 1989*a*).

Gains in N use efficiencies and consumption might involve altering timing and dose strategies but disagreement exists on how that is best achieved. In regions of Europe, up to four separate N applications are performed to supply winter wheat N requirements. However, studies suggest that this is unnecessary and instead recommend a split application where N is supplied at planting and once during tillering/stem elongation (Schulz et al. 2015). In the Prairie region of Canada, earlier N management reports related to crop responses were based on the now obsolete N form ammonium nitrate. With ammonium nitrate removed from the marketplace in Canada, subsequent studies shifted to urea and enhanced efficiency fertilizers (EEF). Although urea is not as readily plant-available as ammonium nitrate, urea has been reported to achieve similar grain yield when applied at planting or broadcast in spring (Irvine et al. 2010).

Enhanced efficiency fertilizers are designed to mitigate losses when applied in conditions prone to losses. In winter wheat production systems, these losses are likely greater than spring annual crops given the longer life cycle of winter wheat. Moreover, studies report volatilization losses can even occur in cool soils (Engel et al. 2011). Surface applications of polymer-coated urea (PCU) or N-butyl thiophosphoric triamide (NBPT) have been reported to reduce ammonia volatilization losses in soil conditions ranging from dry and acidic (Rochette et al. 2009) to cold and wet (Engel et al. 2011). A yield advantage of up to 10% in canola was observed in 6 out of 20 site–years by substituting urea with Environmentally Smart Nitrogen® (ESN) (Blackshaw et al. 2011). Given that these responses were observed in an array of environmental conditions across multiple crops in the northern Great Plains, EEF could be more widely adopted in modern cropping systems. Winter wheat has the potential to integrate this technology successfully as the crop possesses the highest yield potential of all wheat classes, which is likely the driver needed to offset the added input costs unless producers in the future receive carbon tax credits for using technologies that can reduce greenhouse gas emissions and carbon footprints.

Although multiple forms of EEF are available to producers, additional information is lacking regarding changes to EEF efficacy when timing and placement of N is modified to suit specific N management strategies in winter wheat systems. We therefore developed a study to enhance integrated nutrient management systems for winter wheat. The objectives were to (*i*) identify fertilizer management practices that maintain yield and improve protein content to increase the frequency of achieving Select grade (min. 110 g kg^{-1}) of high-yielding winter wheat, and (*ii*) determine if N management practices differ when trying to optimize yield and starch characteristics in soft white winter wheat for use as an ethanol feedstock.

Materials and Methods

Site description and experiment design

This study consisted of two experiments each conducted at the same sites (location × year combinations) (Table 1). In Experiment 1, we investigated the influence of winter wheat variety, N form and application time/placement on winter wheat production. Experiment 2 was developed to study the influence of N form and the timing of in-crop N application. Sites were established on a new study area each year (fall of 2007–2009) at all locations for both experiments. Table 1 provides a summary of the characteristics for each site; Experiment 1 included 15 sites and Experiment 2 included 12 sites.

Experiment 1

The treatment structure consisted of a factorial arrangement of two winter wheat cultivars and 14 N management treatments based on urea type and application time/placement. There were two cultivars selected, AC Radiant (CWRW, milling quality variety) and CDC Ptarmigan (Canada Western Special General Purpose, soft white winter wheat variety, ethanol feedstock). The N management treatment included the following urea types: (*i*) uncoated urea (46–0–0), (*ii*) ammoniacal N stabilized with a urease inhibitor NBPT (Agrotain®), (*iii*) supergranulated urea with increased N stability derived from urease and nitrification inhibitor (SuperU®), (*iv*) PCU — ESN, and (*v*) urea ammonium nitrate (UAN; 28–0–0); only included at Lethbridge. All fertilizer was supplied by Agrium and Koch Agronomic Services. The N fertilizer rate for all treatments was based on 80% soil test recommendation from Western Ag Labs Plant Root Simulator® (PRS; Saskatoon, SK). Each urea type was applied using the following timing/placement methods: (*i*) all N side-banded at time of seeding, (*ii*) all N broadcast in early spring at approximately Zadoks growth stage 30, and (*iii*) half N side-banded and half N broadcast in spring. The N management treatment also included a control (no N fertilizer) and a urea, side-banded treatment applied at a rate based on traditional soil test method and analysis, which was based on a 0–60 cm soil core extraction.

The experimental design for Experiment 1 was a randomized complete block that utilized a split-plot arrangement with four replications. The main plots were cultivars and subplots N management treatment combinations, for a total of 32 treatments. Subplot experimental unit dimensions were about 3.7 m wide × 15.2 m long.

Experiment 2

The treatment design included 17 N management treatments based on urea type and various split application time/placement possibilities. The urea type consisted of (*i*) urea, (*ii*) Agrotain®, (*iii*) SuperU®, and (*iv*) ESN; described in more detail in Experiment 1. The split application time/placement methods portion of the N management treatment included (*i*) all N side-banded at time of seeding, (*ii*) half of the N side-banded and the other half broadcast in the late fall (i.e., first week of November), (*ii*) half of the N side-banded and the other half broadcast in the early spring (Zadoks 30), (*iv*) half of the N side-banded and the other half broadcast mid-spring (Zadoks 40), and (*v*) half of the N side-banded and the other half broadcast in the late spring (Zadoks 45–50). The N fertilizer rate for all urea type treatments were based on 80% soil test recommendation to ensure notable N responses, which utilized the Western Ag Labs PRS soil test system. In addition to the factorial combination of urea type and split application time/placement treatments, a control (no N fertilizer) was included. The winter wheat cultivar for this test was AC Radiant (CWRW, milling quality select variety).

The experimental design was a four-replicate randomized complete block design. Plot dimensions were about 3.7 m wide × 15.2 m long.

Seeding operations and pest management

For both tests, glyphosate or Pre-Pass® (florasulamSC—4.95 g a.i. ha^{-1}; glyphosate—445 g a.e. ha^{-1}) (Dow AgroSciences, Calgary, AB) was applied across the entirety of each site 24–48 h prior to seeding using a motorized sprayer calibrated to deliver a carrier volume of 45 L ha^{-1} at 275 kPa pressure. Seeding was conducted with a ConservaPak™ air drill configured with knife openers spaced 23 cm apart. Winter wheat was sown at a rate of 450 seeds m^{-2}, with a target plant density of 338 plants m^{-2}. Seeding dates for each site in both experiments are summarized in Table 1. All plots, including the control, received blanket applications of other macronutrients based on Western Ag Labs PRS® soil test system.

Table 1. Site description of two tests conducted in MB, SK, and AB, Canada, from fall 2006 to 2010.

										May to August										Yield		
Location/ year	Latitude, longitude	Soil zone	Soil organic matter (g kg^{-1})	pH	Clay (g kg^{-1})	Silt	Sand	1 May min. soil T (°C)	1 May max. soil T (°C)	Precipitation (mm)	Mean air T (°C)	GDD0	Extreme max. T (°C)	Extreme min. T (°C)	Days max. T > 30 ° C	Previous crop	Seeding date	Harvest date	Soil test N (kg N ha^{-1})	AC Radiant (Mg ha^{-1})	CDC Ptarmigan	Experiment 2—AC Radiant
Brandon																						
2007	49°49′N, 99°57′W	Black	50	8.09	330	330	340	—	—	330	15.4	1895	33.2	0.8	7	Barley Silage	13 Sep. 2007	21 Aug. 2008	—	3.91	5.30	—
2008	49°49′N, 99°57′W	Black	50	8.09	330	330	340	—	—	203	14.5	1787	33.8	−1.8	4	Barley Silage	10 Sep. 2008	11 Sep. 2009	—	2.70	2.50	3.01
2009	49°49′N, 99°57′W	Black	50	8.09	330	330	340	—	20	336	16.1	1978	33.5	3.1	8	Barley Silage	17 Sep. 2009	19 Aug. 2010	—	4.33	5.64	4.48
Canora																						
2008	51°37′N, 102°26′W	Black	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	5.73	6.49	5.28
2009	51°37′N, 102°26′W	Black	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.86
Hallonquist																						
2008	50°16′N, 107°46′W	Brown	34	6.51	182	504	314	2	5	158	14.6	1795	33.1	0.4	6	—	25 Sept. 2008	26 Aug. 2009	—	2.26	2.45	2.64
2009	50°16′N, 107°46′W	Brown	34	6.51	182	504	314	3	4	412	14.4	1766	32.8	0.7	3	—	23 Oct. 2009	29 Aug. 2010		2.30	2.38	3.10
Scott																						
2007	52°17′N, 108°57′W	Dark Brown	40	5.9	370	420	310	6	8	206	14.8	1813	34.2	−4.2	3	Canola	7 Sept. 2007	5 Sept. 2008	—	5.07	5.38	4.92
2008	52°17′N, 108°57′W	Dark Brown	40	5.9	370	420	310	4	8	152	13.6	1674	31.4	−5.7	3	Canola	5 Sept. 2008	1 Sept. 2009	—	2.17	2.20	2.26
2009	52°17′N, 108°57′W	Dark Brown	40	5.9	370	420	310	5	6	458	13.9	1710	30.5	−4.1	0	Canola	10 Sept. 2009	25 Sept. 2010	—	5.48	6.41	5.49
Lethbridge																						
2007	49°41′N, 112°45′W	Dark Brown (soil order: Typic Boroll)	30	8	330	300	370	9	15	323	15.8	1942	36.6	4.3	11	Canola	1 Oct. 2007	20 Aug. 2008	—	4.38	3.93	4.00
2008	49°41′N, 112°45′W	Dark Brown	30	8	330	300	370	4	13	234	15.1	1862	33.3	0.3	7	Canola	18 Sept. 2008	27 Aug. 2009	—	3.20	3.67	3.04
2009	49°41′N, 112°45′W	Dark Brown	30	8	330	300	370	—	8	209	14.5	1702	32.7	4.3	6	Canola	16 Sept. 2009	25 Aug. 2010	—	4.76	4.82	5.12
Lacombe																						
2007	52°28′N, 113°44′W	Black	83	6.4	210	330	460	4	6	291	13.7	1688	31.1	2.5	4	Canola	10 Sept. 2007	11 Sept. 2008	—	7.58	9.23	—
2008	52°28′N, 113°44′W	Black	83	6.4	210	330	460	2	5	222	12.9	1589	31.4	−2.9	3	Canola	4 Sept. 2008	10 Sept. 2009	—	6.94	7.97	—
2009	52°28′N, 113°44′W	Black	83	6.4	210	330	460	5	8	460	12.7	1563	29.7	−1.6	0	Canola	9 Sept. 2009	9 Sept. 2010	—	5.45	5.98	—

Weed control was achieved with an application of 2,4-Dichlorophenoxyacetic acid (2,4-D Ester LV 600, 560 g a.e. ha^{-1}; Nufarm Americas Inc., Burr Ridge, IL) when the average growth was the three- to five-leaf stage around mid-October. If necessary, a tax mix of thifensulfuron/tribenuron (15 g a.i. ha^{-1}—Refine Extra®, Dupont Canada Agricultural Products, Mississauga, ON) and clodinafop (56 g a.i. ha^{-1}; Horizon® 240 EC, Syngenta Crop Protection Canada, Guelph, ON) Horizon™ plus Refine Extra™ was applied in the spring for additional weed control. All postemergence herbicide applications were made using a motorized sprayer calibrated to deliver a carrier volume of 45 L ha^{-1} at 275 kPa pressure.

Both cultivars used in this study were susceptible to leaf spot disease complex and rust. Therefore, the lower leaves were monitored and fungicides were applied as needed. Stratego™ (propiconazole, 62.375 g a.i. ha^{-1}; trifloxystrobin, 0.375 g a.i. ha^{-1}; Bayer Crop Sciences, Calgary, AB) was applied to control these foliar diseases when disease progression from the lower to upper leaves indicated that flag and penultimate leaves appeared vulnerable. All fungicide applications were made using label-recommended rates with a motorized sprayer calibrated to deliver a carrier volume of 45 L ha^{-1} at 275 kPa pressure.

Data collection

Winter wheat plant counts were performed in late October to early November in two adjacent, 1-m sections of row located at the fore and aft of each plot, which were marked for future sampling. In early May, plant counts were performed destructively from the marked areas in the front section of the plot to assess winter survival. Heads were counted in early July in the marked rows of the rear section of the plot.

Mid-season plant N status was assessed from Zadoks growth stage 30 to fully emerged flag leaf (2–3 reading over the plots during that time frame) using three different methods. The Greenseeker active lighting optical sensor (NTech Industries Inc, Ukiah, CA) consists of two diodes that emit energy in 671 and 780 nm wavelengths. The light reflected back from the crop is measured by a photodiode and the normalized difference vegetation index (NDVI) is computed $[(R_{780} - R_{671})/(R_{780} + R_{671})]$. The NDVI from the Greenseeker relates to greenness (i.e., chlorophyll levels) and canopy size, and thus the crop N status. Greenseeker readings were collected from plots at all locations in 2008 and 2009 at Zadoks growth stages 30–37. The Field Scout CM1000 chlorophyll meter (Spectrum Technologies, Plainfield, IL) was used to assess chlorophyll levels at Zadoks 30–37 at 2009 locations. The chlorophyll meter measures ambient and reflected light at wavelengths of 700 and 840 nm, which are then used to estimate the quantity of chlorophyll in leaves. Chlorophyll *a* absorbs 700 nm light and light at a wavelength of 840 nm is unaffected by leaf chlorophyll content. The contrasting reflection of light at these two wavelengths is used to make the assessment of the amount of chlorophyll. Leaf area index was assessed within 2 h of solar noon using the LP-80 AccuPAR Ceptometer (Decagon Devices, Pullman, WA), which measures light in the 400–700 nm (PAR) wavelength band. The ceptometer was mounted above the canopy on a leveled tripod in a location between the rows with an unobstructed view of the sky and the crop canopy.

The aboveground biomass from three adjacent 0.5-m row sections was harvested in each plot near physiological maturity (seed difficult to dent with thumb nail). The crop and weed species were separated and the samples dried at 60 °C, which were then threshed to obtain crop and weed biomass values. A subsample of straw was retained, ground through a No. 3 Wiley Mill to pass through a 1-mm diameter screen, and analyzed for N concentration using the Kjeldahl procedure (AACC International 2018*a*).

The entire plot was harvested with a plot combine equipped with a straight-cut header, pickup reel, and crop lifters. Grain yield was calculated and corrected to 13.5% moisture from the entire plot area, from which a 2 kg subsample was retained to characterize seed weight (g 1000 kernels^{-1}), test weight (kg hL^{-1}), and dockage (extraneous plant, insect, or other material in the harvested seed). Whole grain protein concentration was determined from the same subsample using near-infrared reflectance spectroscopy technology (Foss Decater GrainSpec). Starch concentration was determined using the AACC approved method 76.13 (AAAC International 2018*b*).

Calculated data

The efficiency of N fertilizer applications was assessed using the agronomic efficiency of the applied nutrient parameter [AE: $(Y - Y_0)/F$] as defined by Snyder and Bruulsema (2007), where Y is the grain yield (kg ha^{-1}), Y_0 is the grain yield (kg ha^{-1}) without N fertilizer, and F is the N fertilizer rate (kg N ha^{-1}). Apparent crop recovery efficiency of applied N fertilizer (RE) was calculated as follows:

$$\mathrm{RE} = (\text{Total N uptake with N fertilizer applied} - \text{total N uptake without N fertilizer applied}) / \text{N fertilizer rate}$$

Net return data were calculated for both experiments to assess the economic viability of N management treatments. Net return calculation was done on a per-plot basis using the following equation, adapted from Mason et al. (2007) and O'Donovan et al. (2001):

$$\mathrm{NR} = (Y \times P) - (F \times N)$$

where NR is the net return in \$CAD per hectare, Y is the crop yield (Mg ha^{-1}), P is the commodity price in \$CAD Mg^{-1}, F is the cost of each urea type in

\$CAD Mg^{-1}, and *N* is the fertilizer rate (190 kg N ha^{-1}). Commodity prices were obtained from the Canadian Wheat Board historical payments for the respective years. Prices were adjusted for crop class (AC Radiant = CWRW No. 1 or CDC Ptarmigan = CWFW), and AC Radiant commodity price (net returns) was adjusted for protein concentration. Urea costs (\$CAD Mg^{-1}) were as follows: urea = \$838, Agrotain = \$918, SuperU® = \$968, ESN = \$963, and UAN = \$900.

Statistical analysis

Data from Experiment 1 and Experiment 2 were separately analyzed with the GLIMMIX procedure in SAS (Littell et al. 2006; SAS Institute 2011*a*). These mixed models considered the effects of replicate and site (location × year combinations) as random, and the effect of winter wheat variety and N treatments as fixed. Exploratory analyses revealed that residual variances were heterogeneous among sites. The corrected Akaike's information (AIC_c) model fit criterion confirmed whether the preceding model parameterization was better than a model not modeling residual variance heterogeneity. Variance heterogeneity was modeled for all analyses using the random statement for PROC GLIMMIX. The _RESIDUAL_ keyword designated that the residual be modeled and group option set to site to model a separate residual for each site.

Covariance estimates for the overall effect of site, site × variety (Experiment 1 only), and site × variety × N fertilizer form by placement/timing were assessed with a statistical test to determine if the variance estimate was different than zero. Data from each test were analyzed two ways. The first analysis was conducted with a single N management treatment including the control (no N fertilizer) and the urea, side-banded treatment applied at a rate based on a BodyCote (Exova) soil test (Experiment 1 only). Exploratory analyses and AIC_c model fit criterion indicated that it was best to model a separate site variance for each N treatment or variety × N treatment combination (Piepho 1999) rather than model site × N treatment or site × variety × N treatment interactions. It was necessary to estimate covariance parameter estimates in stages. PROC MIXED was used to estimate residual variances for each site. PROC MIXED (Experiment 2) or HPMIXED (Experiment 1) (SAS Institute 2011*b*) was used to estimate site variance for each treatment combination. These covariance estimates from the two separate procedures were "seeded" into a final PROC GLIMMIX analysis using the PARMS statement (SAS Institute 2011*b*).

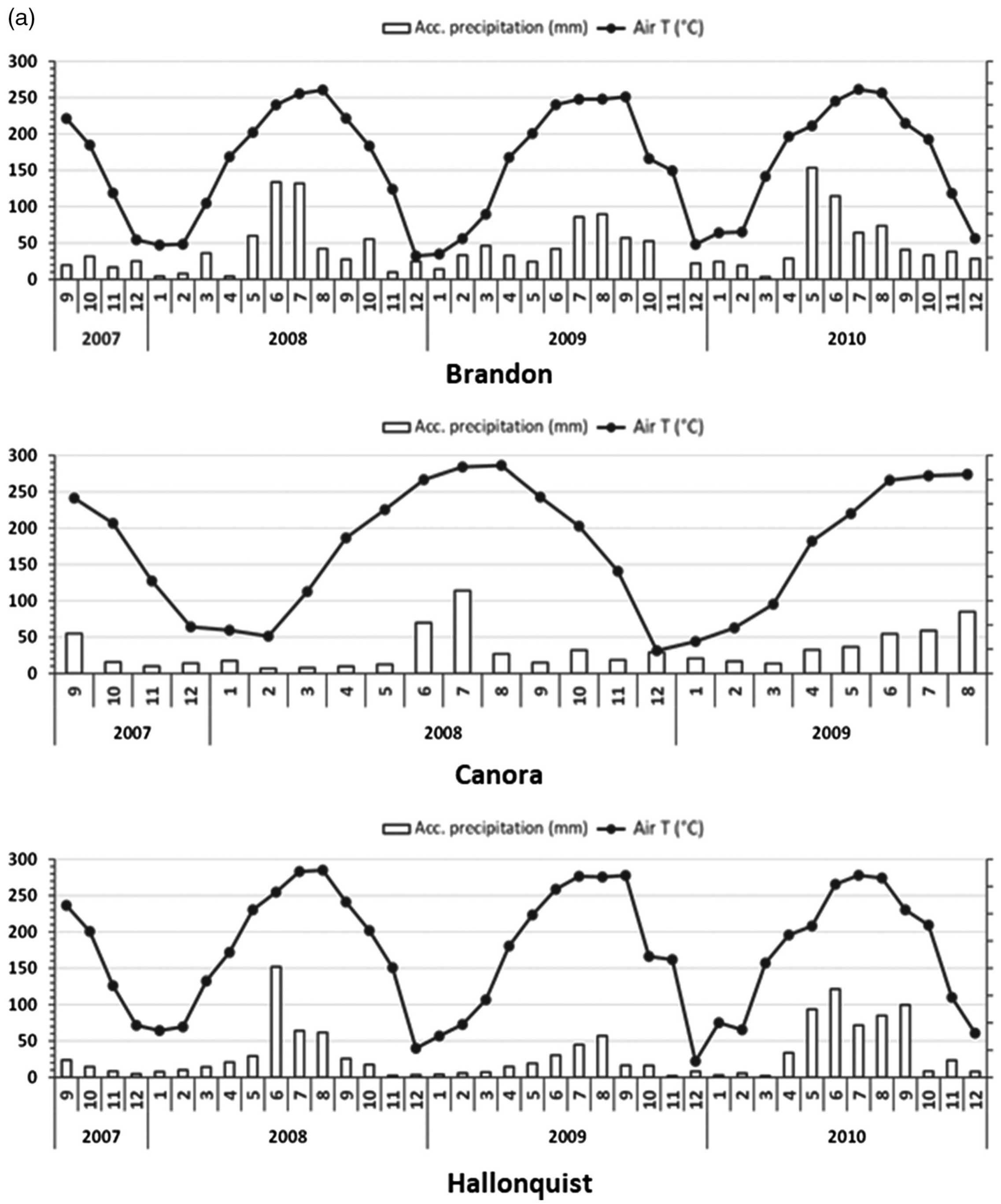
Least square means and covariance parameter estimates from the preceding analysis of variance (ANOVA) were summarized into biplots using a grouping methodology, as previously described by Francis and Kannenberg (1978), and were used to summarize data. The site covariance estimate for each treatment combination was used to calculate the corresponding standard deviation and ultimately the coefficient of variation (CV). Least square means were plotted against CV for each treatment combination for each winter wheat cultivar. The overall mean and CV were used to categorize the biplot data into four quadrants/categories: Group I, high mean, low variability (optimal); Group II, high mean, high variability; Group III, low mean, high variability (poor); and Group IV, low mean, low variability.

The second analysis did not include the control and the urea, side-banded treatment applied at a rate based on the traditional soil test method (Experiment 1 only). This meant that the analysis could consider the factorial treatment design for urea type and application time/placement. In addition, the relative size of the site × treatment variance estimates was compared with the sum of site, site × variety (Experiment 1 only), and site × variety × N fertilizer form × placement/timing interactions. Site × variety and site × variety × treatment interactions deemed important were examined using empirical best linear unbiased predictor (eBLUP) deviations for the difference between the mean at a given site × treatment combination from the overall fixed effect mean for that treatment combination (Littell et al. 2002). A *t* test determined whether each deviation was significantly different from zero. A significant negative deviation means that the treatment combination was lower at a particular site than the mean of the treatment combination averaged over all the sites. The reverse was true if the result was a significant positive deviation.

We determined the relative effect of site–environment indicators (predictors) on winter wheat yield and protein concentration using the partial least squares (PLS; projection to latent structures) method. Data for the analysis consisted of a matrix with each site as a row, and the site–environment predictors and yield/protein means for each site as the columns. The PLS analysis was performed using the PROC PLS procedure of SAS (Tobias 1995; SAS Institute 2011*b*).

Initially, all site–environment indicators were included as predictor variables in the PLS model. From this first PLS analysis, predictors that best explained grain yield were selected based on the criterion of variable importance in the projection (VIP) >0.8 (Wold 1994). The PLS was then rerun with the "important" predictors and restricted to five latent variables (LV); the LV explaining most of the variation. The first LV explains the most variation relative to subsequent LV. Latent variable scores reflect a composite weighting of all measured or recorded site–environmental conditions that potentially influenced winter wheat responses. Correlations between site–environment predictors and the scores for each LV (xloadings) were also estimated. A correlation loading plot provided a way to summarize LV scores and correlations.

Fig. 1. Monthly accumulated precipitation and mean temperature at locations in MB, SK, and AB, Canada, over the course of the study.



Results and Discussion

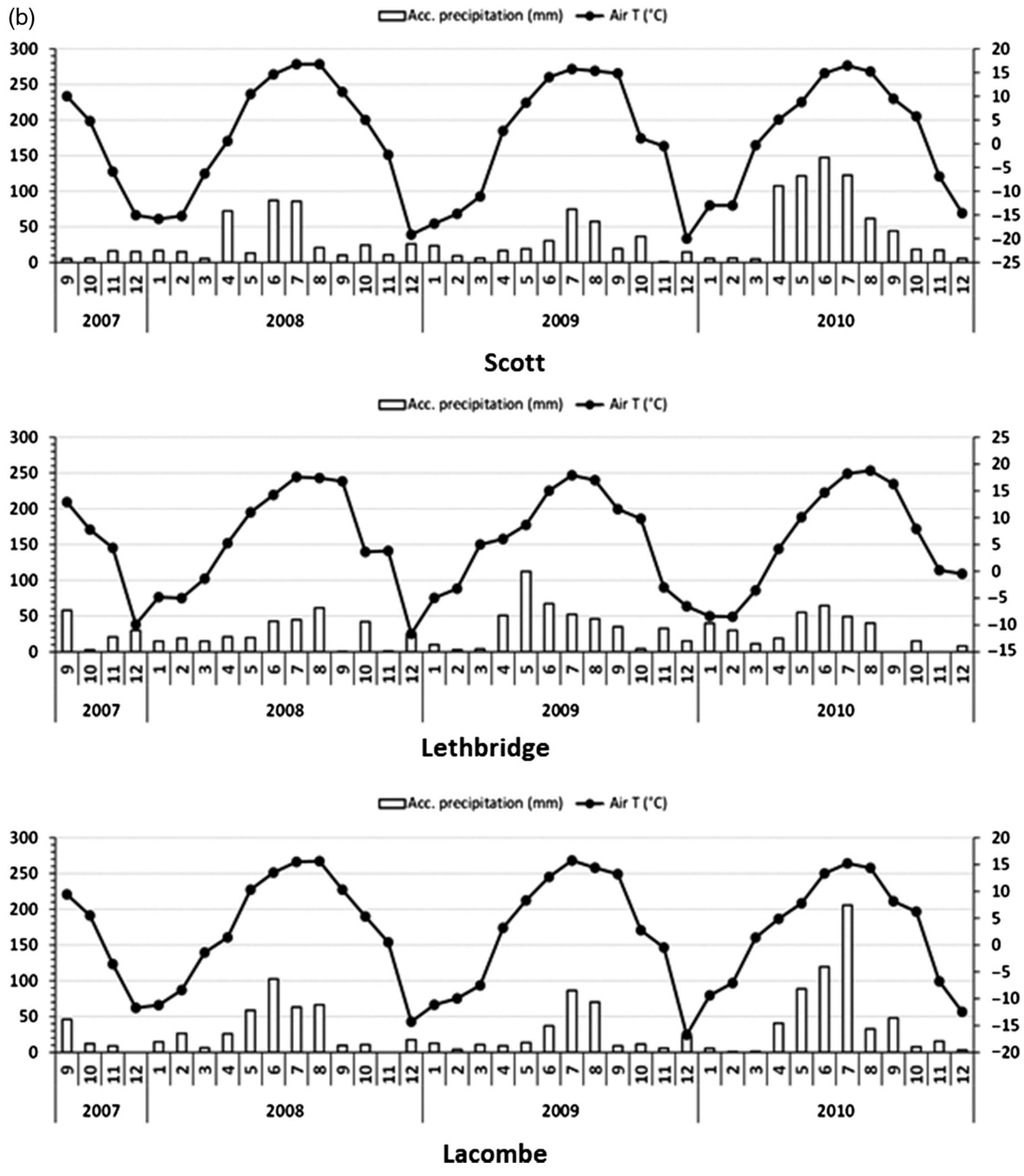
Environmental conditions

A wide range of conditions were encountered over the course of this study (Table 1 and Fig. 1). This type of climatic variation would be considered typical for crop production in the prairies. The most notable aspects of this climatic variation were that eastern prairie locations tended to be cooler during winter months than more westerly locations. Saskatchewan locations tended to be driest during the growing season. Most optimal growing conditions for winter wheat production occurred at Alberta locations with wetter growing season conditions and warmer winter temperatures.

Cultivar differences

Differences between responses of AC Radiant and CDC Ptarmigan were often detected Table 2). The yield of CDC Ptarmigan was 0.55 Mg ha^{-1} greater and starch yield was 0.41 Mg ha^{-1} greater than AC Radiant (Table 2). As

Fig. 1. (*concluded*).



expected, the CWRW protein concentration of the hard red winter wheat cultivar AC Radiant was considerably (15 g kg^{-1}; 1.3%) greater than the soft white winter cultivar CDC Ptarmigan. Inverted yield and protein concentration differences meant that protein yield did not differ between cultivars. Total N uptake for AC Radiant was 7 kg N ha^{-1} greater than CDC Ptarmigan, but AE (agronomic efficiency) and RE (recovery efficiency) did not differ. AC Radiant generated about \$200 ha^{-1} more net returns than CDC Ptarmigan.

The end use of these cultivars will most likely dictate producer choices. The greater protein concentration and profitability of AC Radiant make it particularly suitable as a milling wheat cultivar. Greater grain and starch yield of CDC Ptarmigan make it better suited to the ethanol or feed industry; however, it has also been used in milling applications where soft white wheat flour is desired (D. Hicks, personal communication).

Urea form and placement/timing

A factorial mixed model analysis of the treatments, not including unfertilized control and UAN, was conducted to more easily test for variety, N fertilizer form, and N placement/timing interactions and main effects.

Table 2. Mean responses for winter wheat variety data collected from two tests conducted at sites in MB, SK, and AB, Canada, from fall 2006 to 2010.

	Experiment 1			Experiment 2—AC Radiant		
Variable	AC Radiant	CDC Ptarmigan	LSD0.05	Lower confidence interval	Mean	Upper confidence interval
Spring plant density (no. m^{-2})	223	205	23	174	227	280
Heads (no. $plant^{-1}$)	2.16	2.70	0.31	1.35	2.03	2.71
Grain yield (Mg ha^{-1})	4.50	5.05	0.37	2.82	3.74	4.67
Kernel weight (mg)	37.2	35.9	1.2	35.3	37.3	39.4
Test weight (kg hL^{-1})	78.6	75.4	0.5	76.4	78.5	80.6
Protein concentration (g kg^{-1})	105	90	4	95	106	117
Protein yield (Mg ha^{-1})	0.464	0.446	0.024	0.332	0.414	0.496
Starch concentration (g kg^{-1})	633	627	31	593	623	652
Starch yield (Mg ha^{-1})	2.86	3.27	0.27	1.78	2.46	3.14
Total N uptake (kg ha^{-1})	122	115	5	85	104	124
Agronomic efficiency [kg ha^{-1} (kg N ha^{-1})$^{-1}$]	5.41	7.10	2.33	3.37	5.12	6.86
Recovery efficiency [kg N ha^{-1} (kg N ha^{-1})$^{-1}$]	0.211	0.180	0.034	0.076	0.143	0.210
Net returns (CAN\$ ha^{-1})	1161	973	92	578	812	1046

Spring plant density and protein concentration were not affected by N fertilizer form and placement/timing (Table 3). The main effects of placement/timing and especially N fertilizer form were detected ($p < 0.05$) for winter wheat responses (Table 3). Starch yield was 0.10 Mg ha^{-1} less when N fertilizer was spring broadcast vs. a split application of side banded at planting plus spring broadcast (3.01 vs. 3.11 Mg ha^{-1}; $LSD_{0.05} = 0.08$; data not shown); starch yield for the side-band treatment was intermediate to the other levels of placement and timing.

Variety by N fertilizer form interactions (Table 3) occurred for starch-related variables because starch concentration for AC Radiant was less when ESN® was applied compared with other urea N forms (ESN: 618 g kg^{-1} vs. average of other forms: 638 g kg^{-1}; $LSD_{0.05} = 16$ g kg^{-1}). Starch yield for CDC Ptarmigan was less when ESN was applied relative to other forms except SuperU® (ESN: 3.18 Mg ha^{-1} vs. average of other forms not including SuperU®: 3.39 Mg ha^{-1}; $LSD_{0.05} =$ 0.15 Mg ha^{-1}; SuperU® mean was 3.27 Mg ha^{-1}).

Nitrogen fertilizer form by placement/timing interactions were detected ($p < 0.05$) for other responses, and further exploration of mean differences where interactions were close to statistically significant ($p < 0.20$) indicated that winter wheat yield, heads per plant, kernel weight, and AE and RE responses to N fertilizer form varied among levels of placement/timing (Table 3). The N fertilizer form × placement/timing interactions occurred because N form differences were only significant for the spring broadcast treatment. Mean differences indicated that, for yield-related responses, heads per plant total N uptake, AE, and net returns were less for ESN than the other forms (Table 4). Mean differences indicated that RE was greater for SuperU® than the other forms (Table 4). Conversely, kernel and test weights were greater for ESN vs. one or more of the other forms. In other studies, grain yield and protein concentration in winter wheat were either similar or incrementally favourable for ESN over uncoated urea in regions of the northern Great Plains (Beres et al. 2010*b*; McKenzie et al. 2010).

The variety × N fertilizer form × placement/timing interactions were not quite statistically significant ($p < 0.24$; Table 3), but further examination of mean differences for yield, AE, and net returns indicated that the aforementioned N fertilizer form × placement/timing interaction was most prominent for AC Radiant (Table 4). For CDC Ptarmigan, yield, AE, and net returns were least for ESN® regardless of placement timing N fertilizer form and for spring broad or split applied urea.

Experiment 2 was conducted with selected N fertilizer forms to examine a greater range of split application dates with AC Radiant only. Placement/timing effects were statistically significant for select Experiment 2 winter wheat responses (Table 5). A placement/timing effect was detected for spring plant density and heads per plant; plant density was 239 plants m^{-2} for side-band plus fall-broadcast N and on average 224 plants m^{-2} for other placement/timing levels ($LSD_{0.05} = 9$ plants m^{-2}) and heads per plant was 1.87 heads $plant^{-1}$ for side-band plus fall-broadcast N and on average 2.07 plants m^{-2} for other placement/timing levels ($LSD_{0.05} = 0.14$ plants m^{-2}). This may be an indication that supplemental N at fall provided plant health benefits resulting in improved abiotic resistance and less winterkill. Starch concentration was 597 g kg^{-1} for side-band plus mid-

Table 3. Analysis of variance for winter wheat data collected at Experiment 1 sites in MB, SK, and AB, Canada, from fall 2006 to 2010.

	Spring plant density	Heads per plant	Grain yield	Kernel weight	Test weight	Protein concentration	Protein yield	Starch concentration	Starch yield	Total N uptake	Agronomic efficiency	Recovery efficiency	Net returns
Fixed effects (*p* value)													
Variety (V)	0.105	0.004	0.006	0.033	<0.001	<0.001	0.124	0.674	0.007	0.009	0.141	0.079	0.001
Form (F)	0.243	0.569	<0.001	<0.001	0.045	0.153	<0.001	0.073	0.004	<0.001	<0.001	<0.001	<0.001
V × F	0.816	0.328	0.331	0.304	0.585	0.340	0.985	0.049	0.053	0.434	0.286	0.183	0.642
Placement/ timing (P)	0.431	0.334	0.003	0.255	0.758	0.901	0.040	0.741	0.054	0.743	0.003	0.680	0.001
V × P	0.612	0.855	0.323	0.408	0.329	0.363	0.895	0.984	0.853	0.760	0.350	0.630	0.579
F × P	0.794	0.451	0.139	0.002	0.142	0.475	0.041	0.932	0.783	0.055	0.138	0.074	0.052
Side-band (Sb)	0.311	0.849	0.125	0.908	0.965	0.839	0.149	0.461	0.437	0.692	0.108	0.673	0.115
BC[b]	0.444	0.169	<0.001	<0.001	0.006	0.081	<0.001	0.606	0.030	<0.001	<0.001	<0.001	<0.001
Sb + BC	0.799	0.594	0.079	0.102	0.186	0.362	0.022	0.216	0.163	0.244	0.074	0.212	0.148
V × F × P[a]	0.751	0.354	0.240	0.990	0.871	0.333	0.795	0.541	0.280	0.914	0.244	0.968	0.173
AC Radiant													
Sb	0.817	0.792	0.732	0.757	0.774	0.138	0.645	0.126	0.805	0.554	0.753	0.659	0.437
BC[b]	0.979	0.091	0.003	<0.001	0.061	0.043	0.002	0.320	0.079	<0.001	0.004	<0.001	0.001
Sb + BC	0.602	0.409	0.631	0.128	0.485	0.394	0.217	0.224	0.818	0.424	0.629	0.444	0.632
CDC Ptarmigan													
Sb	0.250	0898	0.004	0.994	0.852	0.662	0.140	0.928	0.068	0.821	0.003	0.816	0.010
BC	0.295	0.643	0.007	0.004	0.105	0.866	0.008	0.967	0.249	0.010	0.006	0.034	0.024
Sb + BC	0.886	0.118	0.071	0.554	0.232	0.583	0.089	0.245	0.044	0.484	0.061	0.477	0.185
Random effects (variance estimate)[c]													
Site (S)	4789**	1.01*	3.46**	6.32*	14.7**	112**	0.0309**	0	1.12**	1460*	9.36*	0.00808*	3776000**
S × V	660*	0.09*	0.18*	2.15**	0.3*	23*	0.0006*	1044**	0.08*	12	4.44	0	106900*
	(12)	(7)	(5)	(2)	(25)	(16)	(2)	(64)	(7)	(1)	(31)	(0)	(3)
S × V × F × P	14	0.02**	0.02*	0.09*	<0.1**	2**	0.0003**	592**	0.02*	23**	0.49**	0.00066**	7239**
	(0)	(2)	(0)	(0)	(1)	(2)	(1)	(36)	(1)	(2)	(3)	(8)	(0)

[a]Contrasts testing the effect of form for each combination of variety by placement/timing.

[b]BC represents spring-broadcast N fertilizer application. Sb + BC is a split application with N side-banded at seeding plus N broadcast in the spring.

[c]The statistical significance of the variance estimates is indicated as follows: *, 0.05 ≥ p value ≥ 0.01; **, p value < 0.01. The site × variety and site× variety × form × placement/timing variance estimates are expressed as a percentage of the sum total variance associated with the effects including site in brackets below the corresponding variance estimate.

Table 4. Mean winter wheat responses to N fertilizer form by placement/timing and variety by N fertilizer form by placement/timing interactions for data collected from Experiment 1 sites in MB, SK, and AB, Canada, from fall 2006 to 2010.

Variable[a]	Agrotain®	ESN	SuperU®	Urea	$LSD_{0.05}$
Heads (no. plant^{-1})					
Sb	2.36	2.43	2.35	2.41	0.19
BC	2.56	2.36	2.41	2.49	—
Sb + BC	2.49	2.40	2.49	2.39	—
Yield (Mg ha^{-1})					
AC Radiant					
Sb	4.55	4.55	4.47	4.47	0.19
BC	4.57	4.26	4.57	4.41	—
Sb + BC	4.56	4.49	4.59	4.48	—
CDC Ptarmigan					
Sb	5.20	4.89	5.13	5.21	—
BC	5.04	4.78	5.09	4.89	—
Sb + BC	5.22	5.00	5.09	4.99	—
Kernel weight (mg)					
Sb	36.5	36.5	36.5	36.6	0.4
BC	36.4	37.3	36.5	36.3	—
Sb + BC	36.5	36.8	36.5	36.3	—
Test weight (kg hL^{-1})					
Sb	77.0	77.0	77.0	77.0	0.2
BC	76.8	77.2	77.0	76.9	—
Sb + BC	77.0	77.0	77.0	76.8	—
Protein yield (Mg ha^{-1})					
Sb	0.465	0.449	0.454	0.462	0.015
BC	0.459	0.433	0.466	0.437	—
Sb + BC	0.467	0.448	0.466	0.450	—
Total N uptake (kg N ha^{-1})					
Sb	119	116	119	118	5
BC	121	112	124	113	—
Sb + BC	121	116	120	118	—
Agronomic efficiency [kg ha^{-1} (kg N ha^{-1})$^{-1}$]					
AC Radiant					
Sb	5.70	5.66	5.28	5.28	1.02
BC	5.82	4.17	5.80	4.96	—
Sb + BC	5.72	5.35	5.90	5.33	—
CDC Ptarmigan					
Sb	7.95	6.27	7.53	7.98	—
BC	7.13	5.69	7.30	6.30	—
Sb + BC	8.08	6.84	7.31	6.86	—
Recovery efficiency (kg N ha^{-1})					
Sb	0.198	0.184	0.199	0.198	0.027
BC	0.210	0.161	0.228	0.174	—
Sb + BC	0.209	0.186	0.209	0.191	—
Net returns (CAN$ ha^{-1})					
AC Radiant					
Sb	1172	1174	1143	1166	42
BC	1169	1093	1173	1154	—
Sb + BC	1177	1159	1184	1165	—
CDC Ptarmigan					
Sb	1001	943	985	1009	—
BC	972	919	978	949	—
Sb + BC	1004	961	982	970	—

[a]Sb represents side-banded and BC represents spring-broadcast N fertilizer application. Sb + BC is a split application with N side-banded at seeding plus N broadcast in the spring.

Table 5. Analysis of variance for winter wheat data collected at Experiment 2 sites in MB, SK, and AB, Canada, from fall 2006 to 2010.

	Spring plant density	Heads per plant	Grain yield	Kernel weight	Test weight	Protein concentration	Protein yield	Starch concentration	Starch yield	Total N uptake	Agronomic efficiency	Recovery efficiency	Net returns
Fixed effects (*p* value)													
Form (F)	0.497	0.677	0.429	0.100	0.295	0.048	0.092	0.377	0.955	0.081	0.419	0.073	0.170
Placement/ timing (P)	0.003	0.007	0.321	0.272	0.159	<0.001	0.006	0.003	0.211	0.282	0.316	0.325	0.318
F × P[a]	0.894	0.608	0.326	0.400	0.973	0.550	0.148	0.849	0.686	0.633	0.329	0.649	0.337
Side-band (Sb)	0.410	0.563	0.936	0.733	0.637	0.431	0.683	0.426	0.695	0.159	0.938	0.126	0.960
Sb + BC[b] Fall	0.962	0.287	0.652	0.777	0.796	0.802	0.521	0.661	0.749	0.071	0.651	0.095	0.622
Sb + BC Early spring	0.912	0.712	0.757	0.031	0.453	0.321	0.824	0.548	0.812	0.891	0.765	0.895	0.514
Sb + BC Mid-Spring	0.325	0.284	0.897	0.270	0.944	0.605	0.548	0.451	0.445	0.900	0.899	0.895	0.920
Sb + BC Late Spring	0.732	0.923	0.013	0.307	0.453	0.021	0.002	0.725	0.361	0.359	0.013	0.349	0.009
Random effects (variance estimate)[c]													
Site (S)	5999*	0.871*	2.06*	8.71*	9.62*	254*	0.0144*	1988*	1.14**	408*	3.49	0.00339	172541**
S × F × P	0	0.01	0.01*	0.15*	0.06**	4	0.0005**	615**	0.01	45**	0.34*	0.00124**	778*
	(0)	(1)	(1)	(2)	(1)	(1)	(3)	(24)	(0)	(10)	(9)	(27)	(0)

[a]Contrasts testing the effect of form for each level of placement/timing.

[b]BC represents spring-broadcast N fertilizer application. All broadcast applications are part of a split application; side-banded N at seeding plus broadcast N.

[c]The statistical significance of the variance estimates is indicated as follows: *, $0.05 \geq p$ value ≥ 0.01; **, p value < 0.01. The site × form × placement/timing variance estimates are expressed as a percentage of the sum total variance associated with the effects including site in brackets below the corresponding variance estimate.

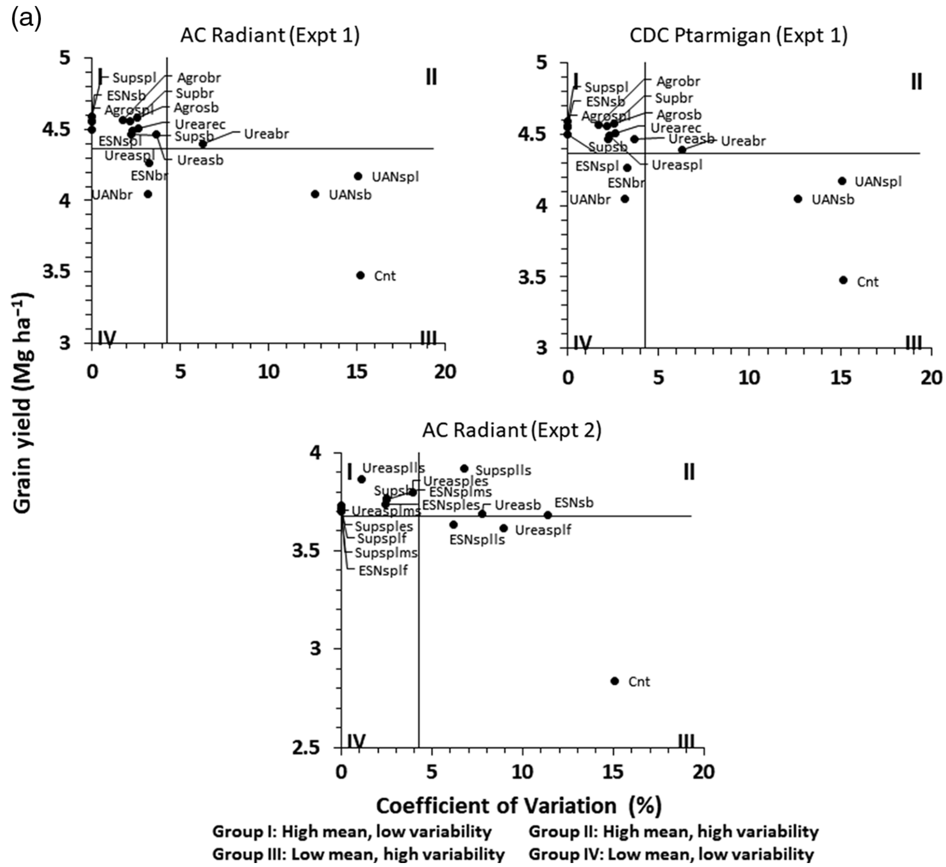
Table 6. Mean winter wheat responses to N fertilizer form by placement/timing interaction for data collected from Experiment 2 (AC Radiant) sites in MB, SK, and AB, Canada, from fall 2006 to 2010.

Variable[a]	ESN	Urea	SuperU®	$LSD_{0.05}$
Yield ($Mg\ ha^{-1}$)				
Sb	3.77	3.74	3.76	0.20
Sb + BC Early Spring	3.74	3.78	3.70	—
Sb + BC Fall	3.65	3.65	3.73	—
Sb + BC Late Spring	3.64	3.84	3.93	—
Sb + BC Mid Spring	3.76	3.72	3.72	—
Kernel weight (mg)				
Sb	37.1	37.0	37.3	0.7
Sb + BC Early Spring	37.9	37.4	37.0	—
Sb + BC Fall	37.0	37.3	37.1	—
Sb + BC Late Spring	37.7	37.3	37.3	—
Sb + BC Mid Spring	37.7	37.4	37.2	—
Protein concentration ($g\ kg^{-1}$)				
Sb	105	106	107	4
Sb + BC Early Spring	107	105	108	—
Sb + BC Fall	103	102	103	—
Sb + BC Late Spring	104	107	110	—
Sb + BC Mid Spring	107	105	107	—
Protein yield ($Mg\ ha^{-1}$)				
Sb	0.403	0.413	0.416	0.031
Sb + BC Early Spring	0.426	0.418	0.421	—
Sb + BC Fall	0.389	0.390	0.404	—
Sb + BC Late Spring	0.392	0.431	0.448	—
Sb + BC Mid Spring	0.426	0.411	0.424	—
Agronomic efficiency [$kg\ ha^{-1}\ (kg\ N\ ha^{-1})^{-1}$]				
Sb	5.25	5.08	5.23	1.04
Sb + BC Early Spring	5.12	5.31	4.91	—
Sb + BC Fall	4.62	4.66	5.04	—
Sb + BC Late Spring	4.57	5.62	6.11	—
Sb + BC Mid Spring	5.22	5.01	5.02	—
Net returns (CAN$ ha^{-1})				
Sb	808	814	812	47
Sb + BC Early Spring	810	830	804	—
Sb + BC Fall	785	795	807	—
Sb + BC Late Spring	782	840	850	—
Sb + BC Mid Spring	818	815	808	—

[a]Sb represents side-banded and BC represents spring-broadcast N fertilizer application, which are part of a split application with N side-banded at seeding.

spring broadcast N and on average 629 $g\ kg^{-1}$ for other placement/timing levels ($LSD_{0.05} = 20\ g\ kg^{-1}$). A priori contrasts were used to test the effect of form for each level of placement/timing in addition to the overall effect due to the interaction of form and placement/timing. Exploration of mean differences associated with the N fertilizer form × placement/timing interaction revealed that the N fertilizer form effect varied among placement/timing levels, despite the ANOVA interaction never being statistically significant ($p > 0.15$; Table 5). For yield, protein-related variables, AE, and net returns, the effect of N fertilizer form was statistically significant ($p < 0.05$) only for side-band plus late spring broadcast N. The N fertilizer form × placement/timing interaction occurred because side-band plus late spring broadcast ESN resulted in lesser responses relative to SuperU® and urea (Table 6), with one exception. Protein concentration for side-band plus late spring broadcast urea was statistically similar and intermediate to other N fertilizer forms. Regular urea has exceeded expectations in many studies as there was an initial concern of high N loss compared with ammonium nitrate, which is no longer available for use. For example, in a spring-broadcast application, urea was less effective than ammonium nitrate in three out of nine trials in a study by Fowler et al. (1989*b*), but equally effective in other studies (Campbell et al. 1991; Middleton et al. 2004; McKenzie et al. 2007; Irvine et al. 2010) despite the

Fig. 2. Biplots summarizing mean vs. CV for combinations of winter wheat variety and N treatment for data collected at MB, SK, and AB, Canada, sites from fall 2006 to 2010. (*a*) Grain yield; (*b*) grain protein; and (*c*) starch concentration. Least square means and CVs calculated from site covariance parameter estimates for each treatment combination. Abbreviations are as follows: ESN = ESN®, Sup = SuperU®, Agro = Agrotain®, Cnt = control, sb = side band, br = spring broadcast, spl = split application with N side-banded at seeding plus N broadcast in the spring, spllf = split application with N side-banded at seeding plus N broadcast in the late fall, sples = split application with N side-banded at seeding plus N broadcast in the early spring, splms = split application with N side-banded at seeding plus N broadcast in the mid-spring, splls = split application with N side-banded at seeding plus N broadcast in the late spring. Grouping categories: Group I, high mean, low variability; Group II, high mean, high variability; Group III, low mean, high variability; Group IV, low mean, low variability.



potential for volatilization losses of ammonia from broadcast urea (Harrison and Webb 2001).

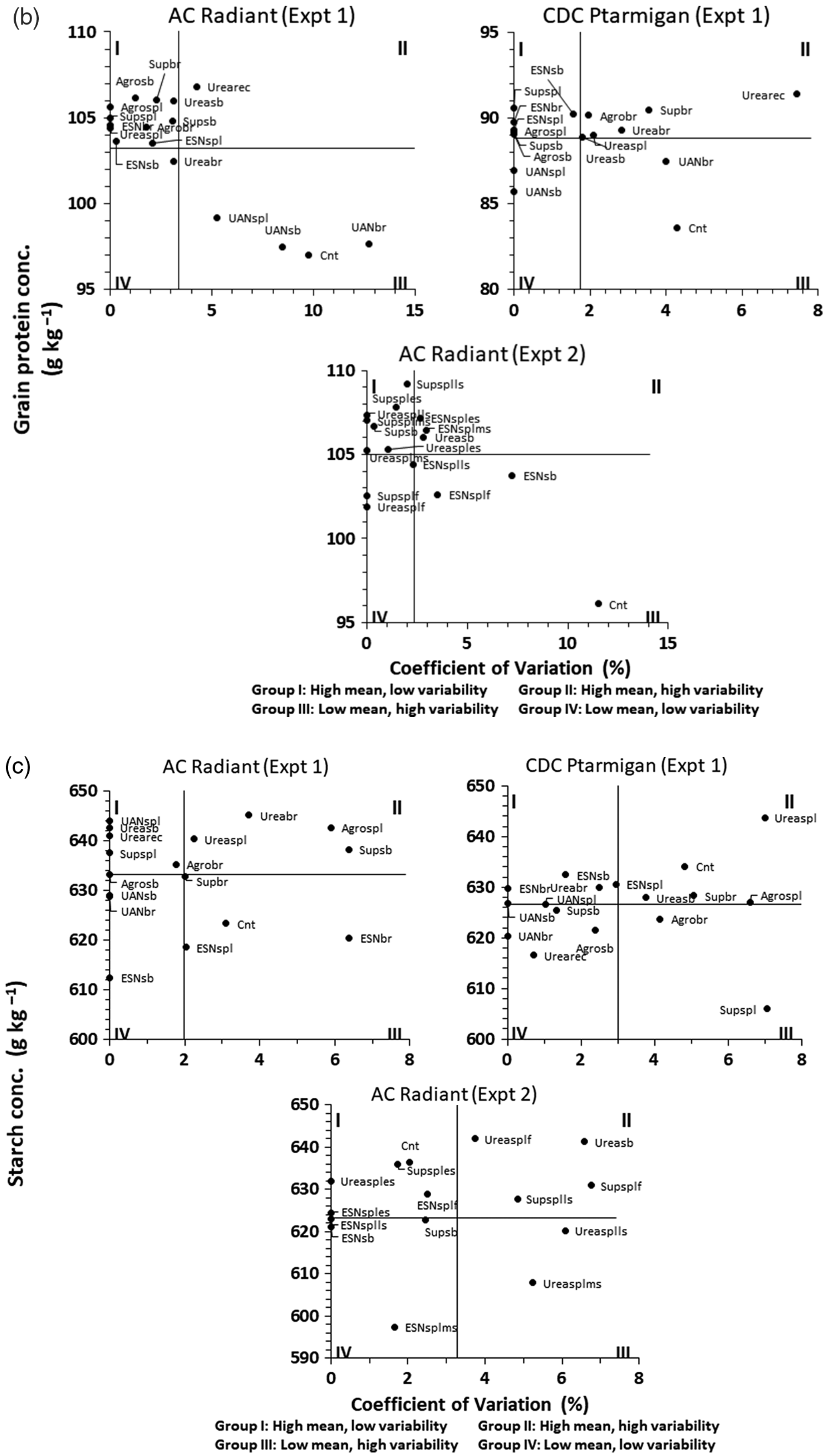
In summary, the results showed that winter wheat stand was not affected by enhanced urea products side-banded during seeding or broadcast in spring when data were averaged across all sites. Total N uptake was less for CDC Ptarmigan, but AE was greater for CDC Ptarmigan. Therefore, CDC Ptarmigan produces greater yields with less N and is thus more efficient relative to AC Radiant (i.e., CDC Ptarmigan was more N efficient at starch production). When different urea-coated products were compared, UAN was clearly inferior from an efficiency and yield standpoint. In addition, ESN caused lower yields, N uptake, starch concentration, and AE, especially for AC Radiant relative to uncoated urea, Agrotain®, and SuperU®. It is thought that the coating characteristics of ESN results in N release patterns that synchronize poorly to the N demands of winter wheat plants, particularly in the northern Great Plains. Results from both tests confirm that the non-ESN urea N fertilizer products can usually be broadcast at different times in the spring or split-applied (broadcast + side-banded during seeding operations) without incurring a yield penalty for both varieties. The simple economic analysis indicated that AC Radiant was more profitable than CDC Ptarmigan, thus indicating the additional protein yield benefits of AC Radiant. CDC Ptarmigan net returns were more sensitive to treatment (e.g., ESN treatments for CDC Ptarmigan had reduced profits).

Variability

Biplots

Mean CV biplots typically are constructed such that the CV includes all random (replicate and site) variability (Francis and Kannenberg 1978). We constructed biplots such that CVs were estimates for variation among sites modeled specially for each treatment from mixed model

Fig. 2. (*concluded*).



analysis (Fig. 2). The value of this approach is that it provides a relatively simple and general overview of system stability, and complements/supplements results for subsequent analyses of the most important response variables such as grain yield and protein/starch concentration.

There were a number of trends that could be derived from the biplots (Fig. 2). The control (no N fertilizer applied) always was positioned in Group III (inferior response and more variable), except for spring plant density. The UAN treatment combinations included in Experiment 1 often occurred in the Group III and IV (inferior response and less variable) quadrants. Starch concentration perhaps was the one response variable that did not follow the preceding trends; where the unfertilized control was not always present in Group III and UAN mainly resided in Groups I or II (greater than average). Our limited assessment of UAN (included as a treatment only at Lethbridge) indicated that it was prone to losses, causing inferior responses. This suggests UAN would probably have benefitted from the inclusion of an N stabilizer. The benefit of treating UAN with NBPT was demonstrated by Grant (2014), albeit not with winter wheat.

There were other treatment combinations that infrequently demonstrated inferior responses (present in the Group III or IV quadrants); e.g., side-banded ESN® for Experiment 2 protein concentration or total N uptake, and split application of urea (half side-banded and half broadcast mid-spring) for Experiment 2 starch concentration.

Optimal responses were observed for a number of the treatment combinations. For example, in Experiment 1, Agrotain® treatments were nearly always present in the Group I quadrant (greater mean and lesser variability) (Fig. 2). Some of the urea, ESN, and SuperU® treatments, in particular for Experiment 2, were present or close to present in the Group II quadrant (greater mean and greater variability); e.g., split SuperU® applications as side-band and broadcast late-spring for Experiment 2 yield. Side-banded urea applied at a rate derived from traditional soil test methods resulted in winter wheat responses similar to other optimal treatments and side-banded urea treatment applied at a rate based on the Western Ag soil PRS® test.

The fixed effects for the portion of the analyses of variance used to compile biplots indicated that all responses except spring plant density and starch concentration were affected ($p < 0.01$) by the N treatment. The variety × N treatment interaction was never statistically significant ($p > 0.44$).

Partial least squares regression analysis

A PLS regression analysis was used to determine the factor(s) controlling yield/protein/starch and overall variability among sites (Vargas et al. 2001). Correlation loading plots derived from the PLS analysis were summarized for each test by variety combination to determine the closeness/oppositeness (correlation) of predictors in relation to yield and protein concentration, and the variance explained by each response/predictor (further to outside of circle means more variance explained (Figs. 3*a*–3*c*).

For Experiment 1 and both varieties, greater total plant N uptake and soil sand content, and to a lesser extent soil organic matter, were associated and may explain the greater yields for both varieties at the Lacombe sites (Figs. 3*a*, 3*b*). Other less-important factors associated with yield (not orientated as close or opposite to yield and positioned further into circle) were greater spring plant density (CDC Ptarmigan only); and crop biomass, soil sand content/soil organic matter content (positively related), and silt content (negatively related). Protein concentration variation for AC Radiant was negatively associated with extreme minimum temperatures. Other factors related to protein concentration were less apparent (ca. 25% variation explained). Greater protein concentration was most associated with the Scott sites, particularly in 2008. The variation of starch concentration in CDC Ptarmigan was not explained well (<25%) by the model. For Experiment 2, lesser AE and greater weed biomass at maturity were related to lesser overall yield for Canora in 2009, and greater AE and lesser weed biomass at maturity were somewhat related to greater overall yield for Scott in 2009 (Fig. 3*c*). Greater AC Radiant protein concentration, especially at Scott in 2007 and 2008, was negatively related to greater extreme minimum temperatures and sand content.

One consistent thread suggested by the PLS analysis was that greater yield tended to always be related to factors associated with N supply (total N uptake) and efficiency (AE), and factors such as soil texture and organic matter that would affect total supply of soil N supplying power. Interestingly, the factor most negatively associated with variation in AC Radiant protein concentration was minimum daily temperatures, which were also identified as an important factor in an analysis of global N response data (Vargas et al. 2001) using a similar approach. These responses may be explained by the fact that average soil temperature will be directly influenced by ambient temperature, and during growth initiation through to the soft dough stage, correlates highly to grain protein in winter wheat (Smika and Greb 1973).

Variance estimates

Although variation associated with site × variety × N treatment interactions for yield was small, it is speculated that if the performance of different urea-coated products did vary then these soil N supplying factors might influence their relative performance. The site × variety × N treatment interactions for starch concentration were always relatively large, but starch concentration variability was not well-explained by the PLS technique. It is thought that starch concentration may

Fig. 3. Partial least squares correlation loading plots for winter wheat and environmental data collected at MB, SK, and AB, Canada, sites from fall 2006 to 2010. Left graph relates to only yield and right graph is a representation for both yield and protein/starch. Green numbers indicate locations. Red letters indicate response variable of interest, purple letters represent winter wheat and environmental parameters.

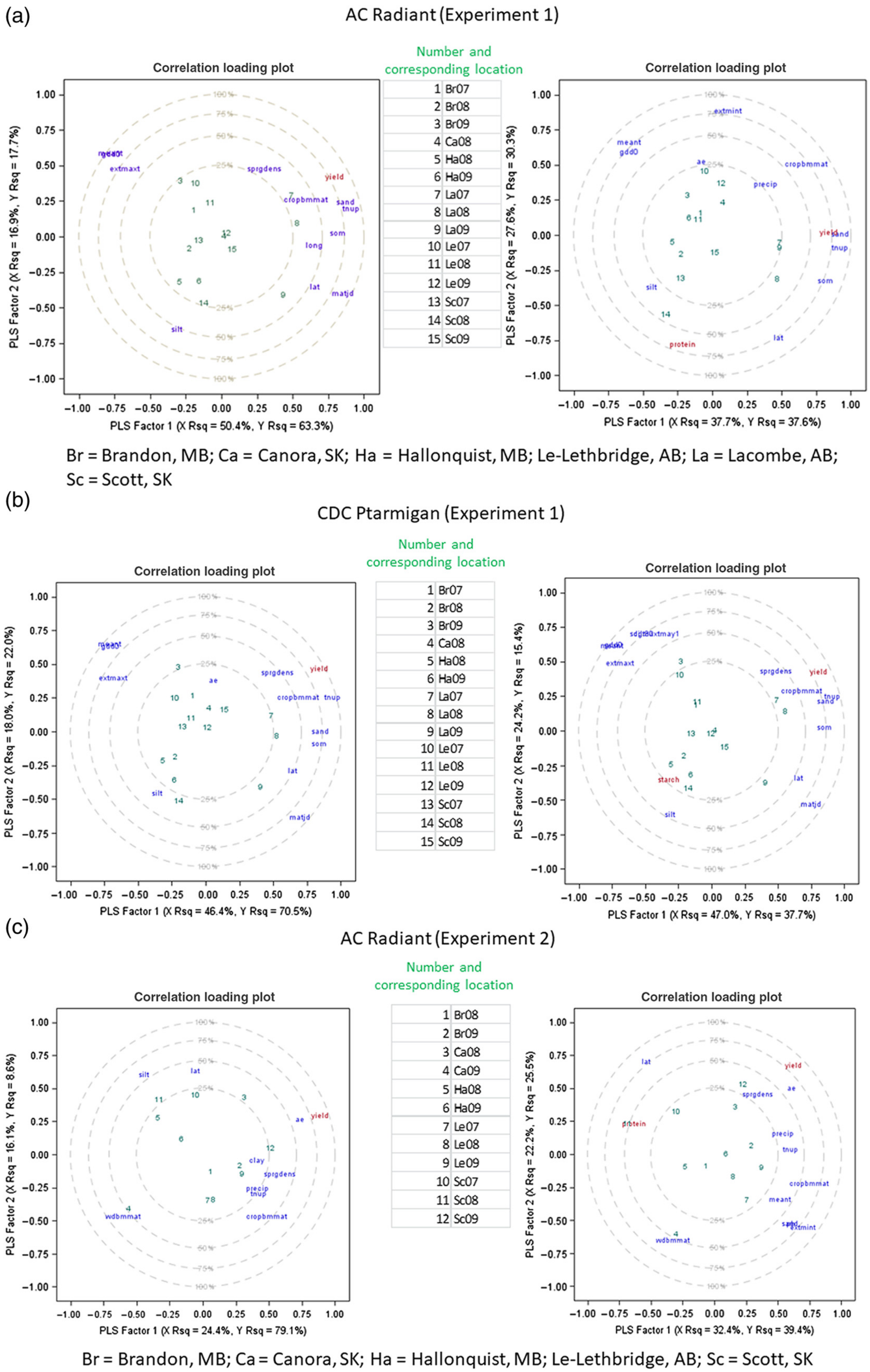


Table 7. Deviations associated with site by variety and site by variety by N treatment interactions for data collected from two tests conducted in at sites in MB, SK, and AB, Canada from fall 2006 to 2010.

Variable	Variety	Placement/timing[a]	N fertilizer form	Deviation[b]		*p* value
Experiment 1						
Agronomic efficiency [kg ha^{-1} (kg N ha^{-1})$^{-1}$] [c]						
Scott 2009	CDC Ptarmigan			3.99	(1.95)	0.072
Protein concentration (g kg^{-1})[c]						
Lethbridge 2007	AC Radiant			−8	(4)	0.047
Lethbridge 2007	CDC Ptarmigan			7	(4)	0.085
Spring plant density (No. m^{-2})[c]						
Lacombe 2008	CDC Ptarmigan			48	(20)	0.031
Starch concentration (g kg^{-1})[c]						
Lethbridge 2009	AC Radiant			−66	(20)	0.051
Scott 2009	AC Radiant			87	(21)	0.011
Starch concentration (g kg^{-1})						
Brandon 2007	AC Radiant	Sb	SuperU	−34	(14)	0.018
Brandon 2007	AC Radiant	Sb + BC	Agrotain	49	(14)	0.001
Brandon 2007	CDC Ptarmigan	Sb + BC	ESN	37	(14)	0.009
Brandon 2007	CDC Ptarmigan	Sb + BC	SuperU	30	(14)	0.034
Brandon 2007	CDC Ptarmigan	Sb + BC	Urea	−47	(14)	0.001
Brandon 2008	AC Radiant	Sb + BC	Agrotain	−44	(14)	0.002
Brandon 2008	CDC Ptarmigan	Sb + BC	Urea	−41	(14)	0.004
Brandon 2008	CDC Ptarmigan	BC	Agrotain	36	(14)	0.012
Brandon 2008	CDC Ptarmigan	BC	SuperU	53	(14)	0.000
Brandon 2008	CDC Ptarmigan	BC	Urea	−30	(14)	0.035
Lacombe 2008	CDC Ptarmigan	Sb	Urea	−41	(16)	0.012
Lethbridge 2007	CDC Ptarmigan	Sb + BC	SuperU	−45	(18)	0.012
Lethbridge 2008	AC Radiant	BC	ESN	−46	(18)	0.011
Scott 2007	CDC Ptarmigan	Sb + BC	SuperU	35	(15)	0.024
Scott 2008	AC Radiant	BC	ESN	33	(15)	0.028
Scott 2008	AC Radiant	BC	Urea	−32	(15)	0.034
Recovery efficiency [kg N ha^{-1} (kg N ha^{-1})$^{-1}$]						
Scott 2008		BC	Urea	0.046	(0.022)	0.045
Scott 2008		Sb	Agrotain	0.051	(0.021)	0.018
Scott 2008		BC	SuperU	−0.039	(0.021)	0.066
Experiment 2						
Starch concentration (g kg^{-1})						
Canora 2008		Sb	Urea	51	(19)	0.010
Hallonquist 2008		Sb + BC Late Spring	SuperU	34	(18)	0.074
Hallonquist 2008		Sb + BC Mid Spring	SuperU	39	(19)	0.039
Scott 2007		Sb + BC Mid Spring	SuperU	−39	(19)	0.051
Recovery efficiency [kg N ha^{-1} (kg N ha^{-1})$^{-1}$]						
Scott 2008		Sb	ESN	0.055	(0.025)	0.032
Scott 2008		Sb + BC Late Spring	SuperU	−0.054	(0.026)	0.051
Scott 2008		Sb + BC Mid Spring	SuperU	−0.050	(0.026)	0.068
Scott 2007		Sb + BC Mid Spring	SuperU	−39	(19)	0.051

[a]Sb represents side-banded and BC represents spring-broadcast N fertilizer application, which are part of a split application with N side-banded at seeding (except for the lone broadcast application for Experiment 1).

[b]Empirical best linear unbiased predictor/deviations (eBLUP) for the difference between the mean at a given site × treatment combination from the overall fixed effect mean for that treatment combination. Standard error for a given deviation is immediately to the right in brackets.

[c]Deviations for site × variety interaction. The remainder of the deviations is for the site × variety (Experiment 1 only) × N treatment interaction.

have other environmental triggers that were not assessed in this study.

For the factorial mixed model variance estimates, the first observation was that site, site × variety, and site × N fertilizer form × placement/timing interactions were often statistically significant ($p < 0.05$) (Tables 3 and 5). The relative size of these was often <10%, with a few exceptions. The site × variety variance estimates for spring plant density, protein and starch concentration, and AE were relatively greater (>10% of overall site variance) (Table 3). Sources for these interactions were determined by exploring deviations at each site from the overall average for each treatment combination. Varietal deviations averaged across N treatments are summarized in Table 7. It seemed that deviations from the overall average for select winter wheat responses mainly occurred for Alberta locations and occurred equally as often for each variety.

The site × variety × N treatment interaction variance estimates for both tests (Experiment 1 was site × variety × N treatment) clearly were more important (>10%) for starch concentration compared with other winter wheat responses (Tables 3 and 5). Deviations (eBLUPs) for each of the variety × N treatments (Experiment 1) at each site from the overall average for each treatment combination are summarized in Table 7. Significant deviations most frequently occurred at Brandon in 2007 and 2008, and most often for CDC Ptarmigan. There was no particular combination of N fertilizer form or placement/timing for which significant deviations occurred, nor were the deviations consistently positive or negative for a given combination of the treatments.

Summary and conclusions

The wide range of environmental conditions (Table 1 and Fig. 1) resulted in a fairly diverse set of site–years that was representative of growing conditions for winter wheat in western Canada. Moreover, the range of growing conditions encountered in this study provided an adequate estimate of how N treatments as designed in the two experiments would affect winter wheat responses in western Canada. Of all the factors tested, varietal differences were most variable among sites. In addition, the control and the most inferior N form, UAN, appeared to be most sensitive to environment variation among sites. With regards to the remaining N treatments, where variety effects, treatment, nor variety × treatment interactions were noted to be deviant at select sites, these deviations were neither frequent nor consistent enough to indicate that average differences among N fertilizer forms and placement/timing would vary among sites. Furthermore, the sites where treatment deviations were detected were not the same sites noted as "unique" sites from PLS analysis (all Lacombe). Productivity levels can vary considerably among the soil zone and potentially affect responses to applied treatments. Yields among soils for both tests in this study were as follows: Brown = 2.6 Mg ha^{-1}, Dark Brown = 4.2 Mg ha^{-1}, and Black = 4.5 Mg ha^{-1}. Based on the results presented here (PLS and eBLUPs), no conclusive evidence suggests that N management with respect to urea type and its placement or timing will differ among soil zones regardless of whether you consider the productivity, quality, efficiency, or profitability of winter wheat. Therefore, we can conclude that Agrotain® and SuperU® may be applied during seeding operations and (or) broadcast in-crop the next spring with reasonably low risk that there would be any yield-related penalty relative to a more typical urea side-banded treatment at the time of seeding regardless of the winter wheat variety. Protein management for winter wheat remains a concern for the industry. An aspect that warrants further investigation is how the influence of daily minimum temperatures identified by our PLS analysis may be used as a management tool to optimize grain protein concentration.

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