Spring Wheat Yield and Quality Related to Soil Texture and Nitrogen Fertilization

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ABSTRACT

Efficient N fertilization is crucial for economic wheat (*Triticum aestivum* L.) production and is of great agronomical and environmental significance. A study was conducted at 12 site-years in eastern Canada to evaluate the effect of soil surface textural groups, N rate (0–200 kg N ha^{-1}) and application timing on grain yield (GY), N uptake, nitrogen uptake efficiency (NUE), grain protein content (GPC), test weight, and thousand kernel weight (TKW). Chlorophyll meter readings (CMR) were taken at tillering and at flowering to assess in-season wheat N nutrition. Fertilization and soil textural group effects were significant on all measured parameters and their interaction was significant on GPC, TKW, test weight, and CMR. Total N uptake and GPC ranged from 39 to 96 kg N ha^{-1} and from 13 to 18 g kg^{-1}, respectively, and total N uptake increased proportionally to N rates. Applying N levels >120 kg N ha^{-1} did not increase total yield, test weight, TKW, or CMR values. The variation in GY, N uptake, and GPC explained by the relative CMR taken at flowering was 87, 88, and 73%, respectively. This study demonstrates that in-season wheat N nutrition can be monitored by CMR and that surface soil texture is an important parameter that influences wheat N response and wheat quality parameters. Applying half of the recommended rate (120 kg ha^{-1}) at planting and the rest at tillering resulted in a high total yield, high grain N uptake, and the highest GPC price premium.

Efficient N fertilization is crucial for economic wheat production and is of great agronomical and environmental significance. Excessive N leads to yield and quality losses due to increased lodging and lower grain test weights or due to overstimulation of plant foliage (Bundy and Andraski, 2004). Excessive N application also increases the potential for nitrate enrichment of ground and surface waters. However, insufficient applied N will cause lower yield and lower GPC, therefore decreasing profits. Wheat producers are interested in wheat grain yield but more importantly in its quality.

The most important wheat quality parameter is grain protein concentration because it affects the milling and baking quality of the grain and because wheat growers generally receive a premium for high protein concentration (McKenzie et al., 2006). Previous studies have reported that the maximum GPC is generally attained at N levels much higher than those required to reach maximum yield (Campbell et al., 1997; Fowler, 2003). Wheat is traded according to several other criteria and different tests have been used as quality parameters. For instance, the test weight is still widely used for price determinations in cereals, although it does not give any indication of flour quality (Kleijer et al., 2007). According to the USDA (1977), a test weight of at least 746 kg m^{-3} is required. However, previous research has shown that the test weight is an unreliable predictor of milling quality (Hook, 1984). Schuler et al. (1994) reported a strong correlation between test weight and flour protein content. Another wheat quality parameter, TKW, measures the mass of the wheat kernel and provides an indication of potential flour extraction. According to Hook (1984), this parameter is influenced by site, year, cultivar, and grain moisture content.

Wheat yield and quality are influenced by many other factors, such as crop rotation and tillage systems (Carr et al., 2008), source of N fertilizer (Yang et al., 2011), and timing of N application (Karamanos et al., 2005). Wheat N requirements are high during tillering, stem elongation, booting, heading, and grain filling for reproductive organ development and for increased protein accumulation in kernel (Delogu et al., 1998). Split application of N fertilizer can help to synchronize N supply with wheat N demand. Because crops, including wheat, remove around 50% (Nyiraneza et al., 2010) of the applied N fertilizer, unused N can be lost through leaching, denitrification, or volatilization.

In view of the importance of synchronizing N fertilizer application with wheat N needs to achieve high grain yield and quality, there is a need for a tool that can accurately assess crop N fertilization status (Ortuzar-Iragorri et al., 2005). Instantaneous and nondestructive chlorophyll meter readings represent an alternative to traditional tissue analysis for diagnosing crop N status and this approach has been used in barley (*Hordeum vulgaris* L.) (Wienhold and Krupinsky, 1999), corn (*Zea mays* L.) (Schepers et al., 1992), rice (*Oryza sativa* L.) (Peng et al., 1993), potatoes (*Solanum tuberosum* L.) (Ziadi et al., 2011), and wheat (Follett et al., 1992; Ziadi et al., 2010). Chlorophyll meter readings are influenced by moisture availability and cultivar differences (Spaner et al., 2005).

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Abbreviations: C, clayey soil; CMR, chlorophyll meter readings; GPC, grain protein content; GY, grain yield; L, loamy soil; Sg, sandy soil belonging to the Gleysolic soil order; Sp, sandy soil belonging to the Podzolic soil order; TKW, thousand kernel weight.

Table 1. Site characteristics and cropping practices.

Sites characteristics	2004				2005				2006			
	Acadie	Acadie	Ste Victoire	Lanoraie	Acadie	Acadie	St. Ours	Lanoraie	Acadie	Acadie	St. Ours	Lanoraie
Location	73°21′09″W; 45°17′39″ N	73°20′25″ W; 45°17′44″ N	73°06′27″ W; 45°55′15″ N	73°19′06″ W; 45°57′03″N	73°20′35″ W; 45°17′52″ N	73°20′13″ W; 45°17′45″ N	73°08′13″ W; 45°54′47″ N	73°19′09″ W; 45°57′00″ N	73°21′19″ W; 45°17′46″ N	73°20′14″ W; 45°17′39″ N	73°07′05″ W; 45°54′53″ N	73°19′06″ W; 45°57′03″ N
Previous crop	soybean	soybean	soybean	potato	soybean	soybean	soybean	potato	wheat	wheat	soybean	potato
Soil series†	St-Blaise	Sabrevois	Massueville	Lanoraie	Bearbrook	Ste-Brigide	Massueville	Lanoraie	Bearbrook	Ste-Brigide	Massueville	Lanoraie
Soil Classification‡	Typic Humaquepts	Typic Humaquepts	Typic Humaquepts	Typic Haplorthods	Typic Humaquepts	Typic Humaquepts	Typic Humaquepts	Typic Haplorthods	Typic Humaquepts	Typic Humaquepts	Typic Humaquepts	Typic Haplorthods
Cation exchange capacity (CEC), cmol kg^{-1}§	19.8	14.3	9.9	9.5	25.8	18.1	11.9	10.5	13.8	13.3	12.2	9.1
Soil organic matter, g kg^{-1}	22	18	43	20	34	28	38	27	24	31	40	24
pH¶	6.8	6.3	6.4	5.9	7.2	7.3	6.4	5.9	6.5	7.0	7.0	6.1
Soil surface-texture#												
Clay content, g kg^{-1}	278	290	88	50	460	186	85	51	220	176	68	50
Silt content, g kg^{-1}	520	417	133	73	461	389	96	58	450	358	102	73
Sand content, g kg^{-1}	202	293	780	877	79	425	820	891	330	466	830	877
Soil textural group	C††	C	Sg	Sp	C	L	Sg	Sp	L	L	Sg	Sp
Temperature (°C)‡‡	6.5	6.5	5.9	5.4	7.5	7.5	7.2	6.6	8.5	8.5	7.8	7.5

† Lamontagne and Nolin (1997).
‡ U.S. soil classification system.
§ Ammonium acetate (pH 7).
¶ pH in water (1:2 soil/water ratio, Hendershot et al., 1993a).
# Hydrometer method after oxidizing the organic matter (Sheldrick and Wang, 1993).
†† C: clayey; L: loamy; Sg: sandy, belonging to the Gleysolic soil order; Sp: sandy, belonging to the Podzolic soil order. Textural groups were determined in the 0 to 0.2 m soil layer.
‡‡ Mean annual temperature.

Wheat N fertilizer is also influenced by weather such as the amount and frequency of rainfall and temperature during the growing season. According to Zhang and Oweis (1999), the sensitive growth stage of wheat to water stress are from elongation to booting, followed by anthesis and by grain filling. Calvino et al. (2003) reported that more than 84% of wheat yield variability was explained by water availability during the period of flowering. Temperature is another important factor that regulates wheat growing. According to Hatfield et al. (2011), rising temperature above 25 to 35°C would shorten the grain-filling period and reduce wheat yield.

Soil surface texture is another important soil parameter that influences crop productivity because of its significant influence on soil organic matter storage (Bird et al., 2000), microbial biomass (Franzluebbers et al., 1996), N mineralization (Hassink, 1994), and crop N requirements (Oberle and Keeney, 1990). For instance, Oberle and Keeney (1990) reported that corn N requirements were lower on irrigated loamy sandy soils than on silt loam soils in a study conducted in the northern U.S. Corn Belt. However, few studies have examined the effects of soil texture on wheat N response (Lehane and Staple, 1965; McConkey et al., 1996). The contribution of soil texture to crop yield variability across the landscape has been reported in previous studies (Cox et al., 2003; Cambouris et al., 2006), indicating the need for variable-rate N fertilization. Others studies, such as those conducted in eastern Canada by Nolin et al. (1989) and Leclerc et al. (2001), have demonstrated that soil texture is the most important component in the soil fertility classification system. To optimize N fertilization in wheat production, it is necessary to have a better understanding of the wheat yield and quality response to N fertilization for different surface soil textures. Our objectives were to (i) assess the effect of soil surface texture and N fertilization (N rate and N timing) on N uptake, N uptake efficiency, wheat yield and grain quality in spring milling wheat production; and (ii) study the relationship between GY, N uptake, and GPC as estimated by relative chlorophyll meter readings taken at tillering (before the second N fertilizer application) and at flowering.

MATERIALS AND METHODS

Site Description and Treatments

A field experiment was conducted over 12 site-years in Québec, Canada: two sites per year at Acadie in 2004, 2005, and 2006; Lanoraie in 2004, 2005, and 2006; Ste.Victoire in 2004; and St. Ours in 2005 and 2006 (Table 1). The selected sites had different surface soil textures: C (clayey), L (loamy), Sp (sandy, belonging to the Podzolic soil order), and Sg (sandy, belonging to the Gleysolic soil order). Soil properties and climatic conditions are presented in Table 1 and Fig. 1. Eight N treatments were considered: N0, N40, N80, N120, N120t, N120s, N160, and N200 kg N ha^{-1}. For the treatments N40, N80, N120, N160, and N200 kg N ha^{-1}, 30 kg N ha^{-1} was broadcast at sowing

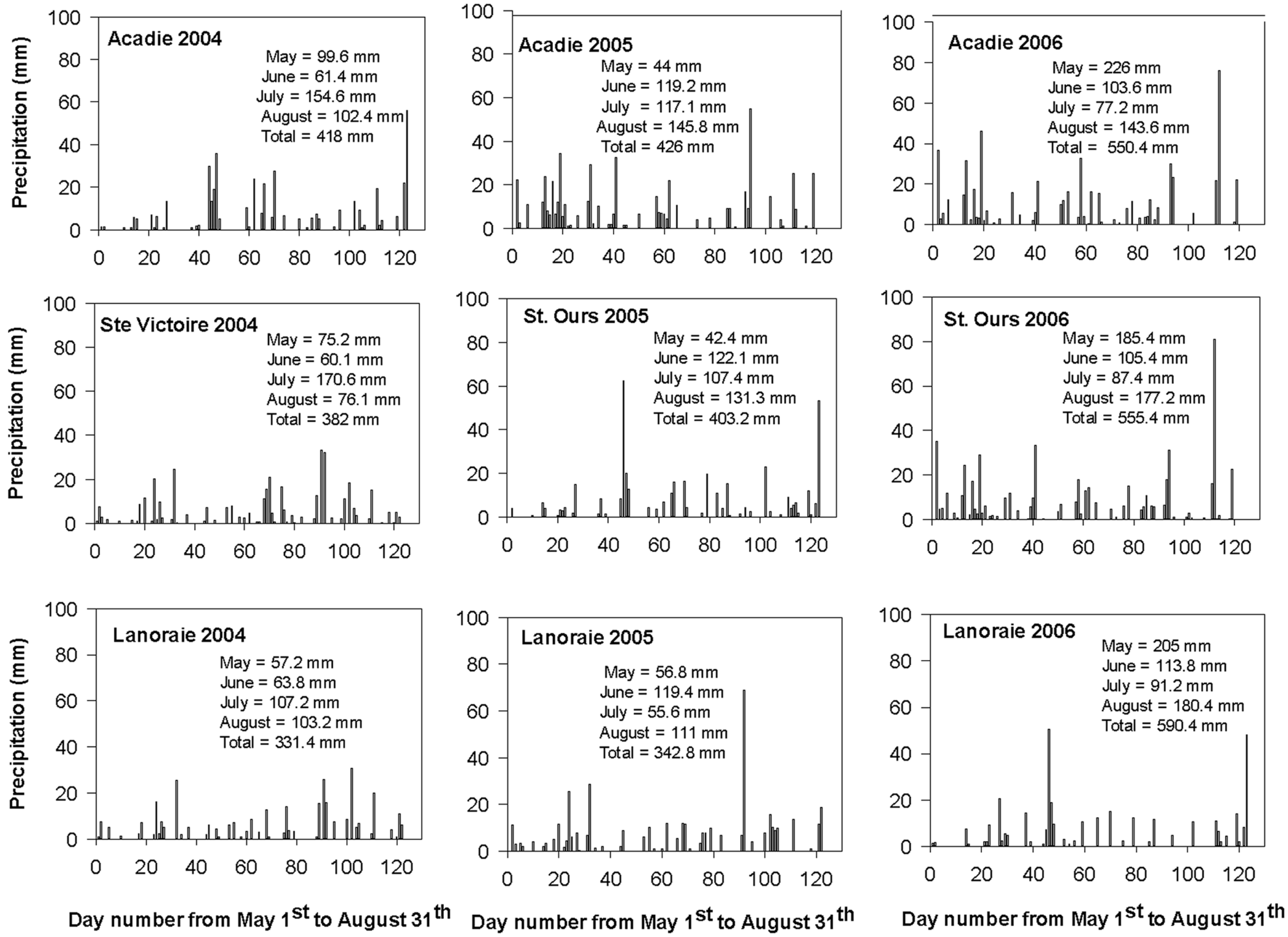

Fig. 1. Rainfall pattern at studied sites. Daily precipitation data were collected at Iberville meteorological station for the sites situated at Acadie; at Joliette meteorological station for the sites situated at Lanonaraie; and at Sorel meteorological station for the sites situated at Ste Victoire and St. Ours.

and the remainder was applied once at stem elongation. For the treatment N120t, 50% was applied at sowing and the rest at the tillering stage (CRAAQ, 2003). For the N120s treatment, 120 kg N ha^{-1} was broadcast applied at sowing. A randomized complete block design with four replicates was used at each experimental site. Ammonium nitrate (34–0–0) was broadcast at planting and calcium ammonium nitrate (27–0–0) was broadcast during subsequent applications. At planting, P and K fertilizers were applied as triple superphosphate (0–46–0) and potassium chloride (0–0–60), respectively, according to soil analysis and local recommendations (CRAAQ, 2003). The experimental unit measured 10 by 10 m, and the cultivar AC Barries, a recommended cultivar for Québec, was sowed at all sites at a rate of 150 kg ha^{-1} with 0.15-m row spacing.

Soil and Plant Sample Collection and Analysis

Before planting, composite soil samples were taken from each site in the surface layer (0–20 cm) for the chemical and physical analyses. Particle-size analysis was performed by the hydrometer method after organic matter oxidation (Sheldrick and Wang, 1993). Organic matter content was determined by wet oxidation (Tiessen and Moir, 1993). Soil pH was measured in distilled water with a 1:2 soil/solution ratio (Hendershot et al., 1993a). Cation exchange capacity was analyzed with the ammonium acetate at pH 7 (Hendershot et al., 1993b).

Grain yield and aboveground biomass were determined in each plot using a plot combine (Wintersteiger, Model NM-Elite) on a 10 m^2 (6.7 by 1.5 m) area located in the middle of each plot. Shoot biomass was weighed fresh, and subsamples of approximately 500 g were collected for analysis. Subsamples were dried at 55°C in a forced-draft oven for 7 d, ground in a Wiley mill to pass a 1-mm screen, and stored at room temperature before laboratory analysis. The grain was dried at 55°C until constant mass was achieved, and the grain yield was adjusted to 13.5% moisture (CRAAQ, 2003). Samples of 0.1 g of dried and ground shoots and seeds were digested using a mixture of sulfuric and selenious acids, as described by Isaac and Johnson (1976). The N concentrations in plant tissue were measured on a Lachat QuikChem 8000 autoanalyzer using Lachat method 15-501-3 (Zellweger Analytics Inc., Lachat Instruments, 2005, Milwaukee, WI). Test weight was determined using the 0.5 L measure according to the method described by the Canadian Grain Commission board (2011) (http://www.grainscanada.gc.ca/wheat-ble/method-methode/wmtm-mmab-eng.htm). Briefly, the grain in the container is poured into the pan of an approved electronic scale for weighing. The computer connected to the scale calculates the test weight of the grain in kilograms per hectoliter from grams weighed by the scale.

Thousand kernel weight was determined for each sample with a seed counter, and the weight was measured on a precision

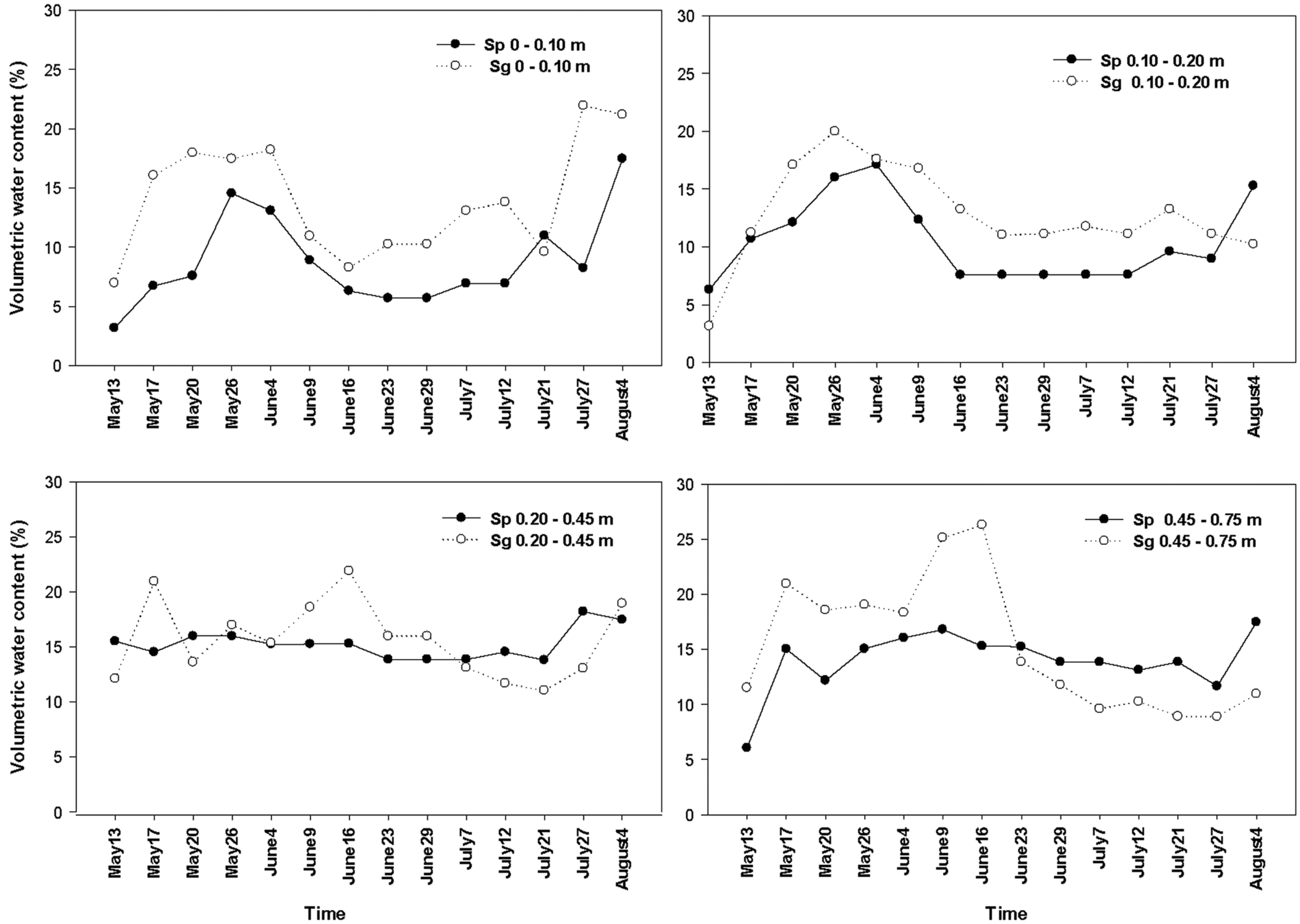

Fig. 2. Comparison of volumetric water content between a sandy soil belonging to podzolic soil order (Sp) and a sandy soil belonging to a gleysolic soil order in 2004 at 0.10-, 0.20-, 0.45-, and 0.75-m depth. Measurements were performed with Time domain reflectometers (TDR model Tektronix 1502C). Textural groups were determined in the 0 to 0.2 m soil layer.

balance. Each measurement was performed in triplicate. Grain protein concentration (GPC) was calculated as the grain N concentration multiplied by 5.7 (g kg^{-1}) (http://www.grainscanada.gc.ca/wheat-ble/method-methode/wmtm-mmab-eng.htm). Total N uptake was calculated by multiplying total N concentration (%) by aboveground dry matter (kg ha^{-1}). Nitrogen uptake efficiency was calculated as follows: (N uptake in fertilized plot– N uptake in the control treatment)/applied N fertilizer.

Chlorophyll content was measured at two different times using a chlorophyll meter (Minolta SPAD-502, Spectrum Technologies Inc., Plainfield, IL). The first measurement was taken at tillering and the second at flowering. The readings were performed on the topmost fully expanded leaf, and readings were taken from a point half the distance between the leaf tip and the collar and halfway from the leaf margin to the midrib (Ziadi et al., 2010). Recorded data consisted of 30 randomly chosen plants, on average, from each plot. Relative CMR was calculated as the ratio between treatment mean CMR and the highest mean CMR.

Statistical Analysis

Analysis of variance was performed using the MIXED PROCEDURE of SAS (SAS Institute, 2004), to assess the effects of fertilization and soil surface texture on wheat yield, N uptake, N uptake efficiency, test weight, TKW, and GPC. Since not all the textural groups were present every year, year-sites served as replicates for textural groups, and fertilization and soil textural groups were treated as fixed effects, while year-site × textural class and block (site-year) were treated as random factors. The relationships between relative CMR and GY, total N uptake, and GPC were assessed using the REG PROCEDURE of SAS (SAS Institute, 2004). The DIFF option of SAS was used to perform a multiple comparison among treatments and when the interaction between main effects was significant, the SLICE statement of SAS was used to partition the interaction.

RESULTS AND DISCUSSION

Characteristics of Studied Sites

Studied sites were located in humid soil moisture regimes with growing season rainfall mean annual temperatures ranging from 5.4 to 8.5°C (Table 1). Rainfall pattern was different each year and across sites (Fig. 1). Overall, year 2006 received more rain than 2005 and 2004, especially in May and August (Fig. 1). June was rainier in 2005 than in 2004, whereas July was rainy in 2004 than July 2005 and 2006 (Fig. 1). Averaged across site-years, C and L textural groups (Acadie sites) received more rain (465 mm) than Sg (Ste Victoire and St. Ours sites) which received an average of 446.9 mm while Sp textural group (Lanoraie sites) received an average of 421.5 mm (Fig. 1). Soil organic matter ranged from 18 to 43 g kg^{-1}, while pH values ranged

Table 2. Effects of soil texture and N fertilization on wheat yield, N uptake, and N uptake efficiency.

Source of variation	Yield straw	Yield grain†	Total yield	Straw N uptake	Grain N uptake	Total N uptake	N uptake efficiency‡
	Mg ha^{-1}			kg ha^{-1}			%
Soil textural group							
C§	3.2b¶	2.1a	5.4b	18.7b	49.1a	67.8b	32.8a
L	4.4a	2.6a	7.1a	26.1a	61.7a	88.4a	38.6a
Sg	2.6c	1.9a	4.5c	22.6a	50.1a	72.7b	33.5a
Sp	2.9c	2.1a	4.9bc	25.6a	51.9a	77.6ab	41.6a
N fertilization							
N0	2.0d	1.5d	3.5d	9.4e	29.7d	39.1e	–
N40	2.7c	1.9c	4.7c	12.6d	41.4c	54.0d	37.2b
N80	3.2b	2.3b	5.5b	22.6c	56.7b	79.3c	50.2a
N120	3.6a	2.3b	5.9a	28.5b	59.7a	88.2ab	40.9ab
N120t	3.6a	2.6a	6.3a	23.3c	63.1a	86.4b	39.4b
N120s	3.5a	2.4ab	5.9a	20.5c	56.1b	76.6c	31.2b
N160	3.7a	2.2b	5.9a	33.2a	59.0a	92.2b	33.2b
N200	3.8a	2.2b	6.0a	35.9a	60.0a	96.0a	28.4c
Analysis of variance (*p* value)							
Texture	<0.001	0.05	<0.01	0.01	0.10	0.0018	0.42
Treatment	<0.001	<0.001	<0.01	<0.01	<0.001	<0.001	<0.001
Texture × Treatment	0.47	0.19	0.20	0.79	0.12	0.11	0.48

† Only the overall means are reported as the interaction between texture and N fertilizer was not significant.

‡ N uptake efficiency was calculated as the difference between total N uptake (straw + grain) in the treatment minus total N uptake in the control treatment divided by N fertilizer applied.

§ C: clayey; L: loamy; Sg: sandy, belonging to the Gleysolic soil order; Sp: sandy, belonging to the Podzolic soil order. Textural groups were determined in the 0 to 0.2 m soil layer.

¶ Means followed by the same letter are not significantly different at 0.05 probability level.

from 5.9 to 7.3. Clay content ranged from 50 to 460 g kg^{-1} and the sand content varied between 79 and 891 g kg^{-1}. Four surface soil textural groups (0–0.2 m) were identified: clayey (C), loamy (L), sandy soils belonging to the Podzolic soil order (Sp), and sandy soils belonging to the Gleysolic soil order (Sg) (Table 1). Podzolic sandy soils are different from Gleysolic sandy soils, as the latter type has a higher water retention capacity and a higher level of soil organic matter than the former (Table 1, Fig. 2). The organic matter content in Sg group ranged from 38 to 43 g kg^{-1} and from 20 to 27 g kg^{-1} in Sp group (Table 1). Figure 2 reports weekly measurements of volumetric water content assessed at 0.10-, 0.20-, 0.45-, and 0.75-m depth in 2004. It is clear that Sg textural group had in general higher water content than Sp group. Spring mineral N (0–0.20 m) was also analyzed and values ranged in this order: Sg > Sp > C > L (Fig. 3) although not statistically significant. The high levels in light textured soils than C and L can probably be explained by the fact that the latter drain slowly and take longer to warm up than sandy ones. The previously grown crops were soybean, potato, and wheat, but soybean was predominant (Table 1).

Effects of Nitrogen Rate and Soil Texture on Wheat Yield, Nitrogen Uptake, and Nitrogen Uptake Efficiency

Nitrogen fertilization had a highly significant effect on almost all measured parameters (Table 2). Wheat grain yield ranged from 1.5 to 2.6 Mg ha^{-1} and the values are comparable to those (1.5–2.9 Mg ha^{-1}) obtained for spring wheat by Manning et al. (2001) in a 2-yr study done in Manitoba, Canada, using N rates varying between 0 and 135 kg N ha^{-1}. Grain yield levels in our study are in the same range but slightly lower than those (1.7–3.6 Mg ha^{-1}) reported by Tran and Tremblay (2000) in a 2-yr study conducted in Québec with N rates ranging from 0 to 180 kg N ha^{-1}. The highest N rate (N200) gave a lower grain yield than N120t which was comparable to that for N80 (Table 2).

Straw N uptake, grain N uptake, and total N uptake tended to increase proportionally to the N rate. However, grain N uptake associated with N200 was comparable to that of N120 and N120t treatments. Total N uptake ranged from 39 to 96 kg N ha^{-1} (Table 2). These values are of the same magnitude as those (53.7–132.7 kg ha^{-1}) reported by Tran and Tremblay (2000;) in Québec, Canada, at N rates varying between 0 and 180 kg N ha^{-1} and those reported by Tiessen et al. (2005; 52.2–124 kg ha^{-1}) in Manitoba at N rate of 80 kg N ha^{-1}. The total N uptake for the N120s treatment was lower than that obtained for the N120 and N120t treatments (Table 2).

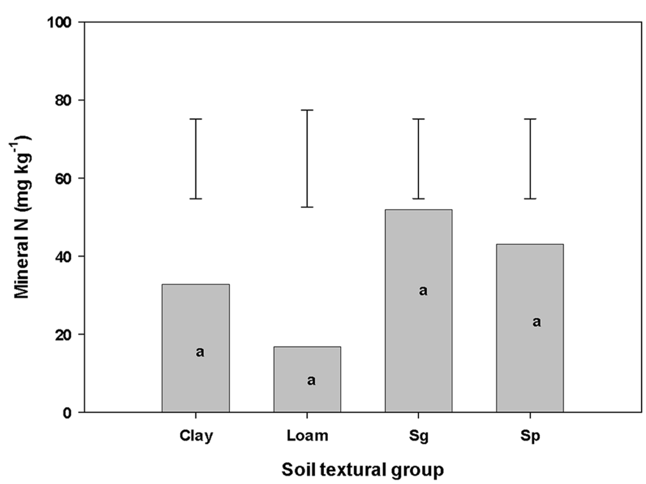

Fig. 3. Spring mineral N (NO_3–N + NH_4–N) (0-0.2 m) content per textural group averaged over site-years. Vertical bars indicate standard error of the mean. Textural groups were determined in the 0–0.2 m soil layer.

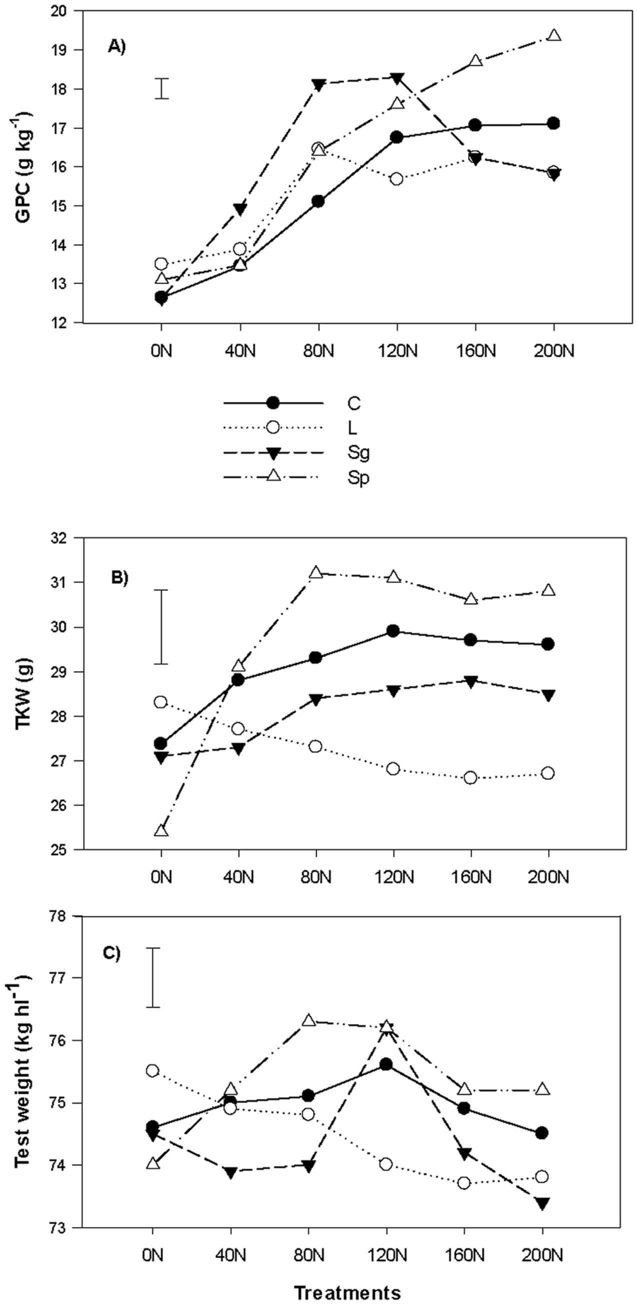

Fig. 4. Influence of soil surface textural groups on: (A) grain protein concentration (GPC); (B) thousand kernel weight (TKW); and (C) test weight. Vertical bars indicate the standard error of the mean. C: clayey; L: loamy; Sg: sandy, belonging to the Gleysolic soil order; Sp: sandy, belonging to the Podzolic soil order. Textural groups were determined in the 0 to 0.2 m soil layer.

The total N uptake efficiency ranged from 28 to 50%. Our data are in the same range as those in the studies reported by Tiessen et al. (2005) and Tran and Tremblay (2000), which reported N uptake efficiency varying from 17 to 55% and from 31 to 52%, respectively. The highest N uptake efficiency was associated with the N80 treatment. Lower values were associated with the highest N rate, which is consistent with the findings of studies on corn (Gagnon and Ziadi, 2010) and potato (Zvomuya et al., 2003). Decreased N uptake efficiency at high N rates indicates that plants cannot use N at the higher rates or that N losses exceed the rate of plant N uptake (Fageria and Baligar, 2005).

Soil surface textural group effect was significant on straw yield, total yield, straw N uptake, grain N uptake, and total N uptake. This is most likely due to the influence that soil texture has on soil physical properties and on nutrient cycling. High values for total yield (7.1 Mg ha^{-1}, overall mean) and total N uptake (88.4 kg ha^{-1}) were found in loamy soils (Table 2). Surface soil texture has been described as an important factor in the formation of soil fertility groups (Nolin et al., 1989; Leclerc et al., 2001). In Québec, the recommended N rate for wheat ranges from 90 to 120 kg N ha^{-1} for fine and coarse-textured soils, respectively (CRAAQ, 2010). Our findings are in line with previous studies which showed that soil texture has a strong influence on crop yield variability (Cox et al.; 2003; Cambouris et al., 2006) and crop N requirements (Oberle and Keeney, 1990).

In addition to yield levels and uptake efficiency, wheat quality parameters are of interest to wheat growers because of their influence on processing quality.

Effects of Nitrogen Rate and Soil Texture on Grain Protein Concentration, Test Weight, and Thousand Kernel Weight

Low GPC is linked to economic losses to wheat producers through denial of protein premiums. Nitrogen is an essential component of grain protein, and therefore N supply to the wheat affects GPC. Grain protein concentration ranged from 12.9 to 17.8 g kg^{-1} (Fig. 4). These values are in the same range as those (13.2–18.2) reported by McKenzie et al. (2006) in a study conducted over 26 site-years in Saskatchewan, Manitoba, and Alberta, Canada, using an application rate of 120 N kg ha^{-1}. Except in the N0 treatment, the GPC obtained was higher than the critical level (13.5 g kg^{-1}) reported for spring wheat in the eastern Canadian prairies (Flaten and Racz, 1997). Nitrogen fertilizer rate effect, soil textural group and their interaction were significant on GPC, TKW, and on test weight (Table 3). The significant interaction means that the effects of N fertilizer on these parameters were different according to the soil type. Grain protein concentration tended to increase proportionally to N rate in clay and Sp textural groups (Fig. 4A). Conversely, high GPC corresponded to N rate of 80 and 120 kg N ha^{-1} and then decreased in loam and Sg textural groups, respectively (Fig. 4A). Previous studies have reported that it may be necessary to apply N fertilizer at rates above those required for maximum grain yield, to obtain the GPC price premium (Fowler, 2003).

According to Fowler (2003) and Palta and Fillery (1993), when available N is insufficient to reach the maximum yield, the N applied at the time of seeding mainly contributes to increasing yield. Late applications are more effective at increasing protein concentration than early applications. By contrast, if available N is sufficient to achieve maximum yield, N applied at seeding will be as effective as N applied later in the growing season. According to McKenzie et al. (2006, 2008), as GPC increases from 11 to 15.5 g kg^{-1}, wheat growers receive an incremental price premium that varies annually depending on market conditions. Therefore, in this study, the split application of N fertilizer at a rate of 120 kg N ha^{-1} was sufficient to maximize yield and attain the GPC level needed for the maximum price premium.

Thousand kernel weight, which measures the mass of the wheat kernel, is used by wheat breeders and flour millers as a complement to test weight to better describe potential flour extraction. The TKW ranged from 27 to 29.7 g 1000 grains^{-1} (Fig. 4B). These values are in the same range but lower than those (26–37 g 1000 grains^{-1}) reported by Melaj et al. (2003) in a study conducted in Argentina on a loamy soil with an N rate of 120 kg N ha^{-1} applied in one or two applications. Our values fall in the lower part of the range (32.5–38.7 g 1000 grains^{-1}) reported by Lukow and McVetty (1991) in an experiment conducted in Manitoba using eight genetically diverse spring cultivars. The N rate effect on TKW was different depending on soil textural group and an increase of TKW was observed up to 120 kg N ha^{-1} for C, Sg, and Sp textural groups while we observed an inverse relationship between N rate and TKW in L textural group. Grain weight is influenced not only by soil properties and N fertilization, but also by environmental conditions, such as temperature, and the pattern of growing degree day accumulation (Melaj et al., 2003).

Test weight (kilograms per hectoliter), which has traditionally been used as a quality parameter of cereals in a large number of countries and is still used to set the price level, is affected by environmental and genotypic factors (Kleijer et al., 2007). Test weight varied between 74.2 and 75.3 kg hL^{-1}. Our values are of the same magnitude as those (66.7–86.2 kg hL^{-1}) reported by Kleijer et al. (2007) but lower than those (76.2–79.6 kg hL^{-1}) obtained by Lukow and McVetty (1991). Applying N levels >120 kg N ha^{-1} did not increase the test weight values (Fig. 4C). In general the maximum test weight was obtained at 120 kg N ha^{-1} in C, Sp, and Sg textural groups and was inversely related to N fertilizer rate in C group (Fig. 4C). Test weight is influenced by environmental factors such as high temperatures during grain filling, rainfall before harvest, and crop diseases (Kleijer et al., 2007). Test weight gives no indication as to whether the tested material consists of well-filled grain, low-density shriveled grain, poorly filled grain, or damaged grain (Schuler et al., 1995). In addition, previous studies have found no relationship between flour yield and test weight (Schuler et al., 1995; Kleijer et al., 2007). Therefore, the usefulness of this test is being called into question (Kleijer et al., 2007). Test weight and TKW decreased as N fertilizer rate was increased in L textural group. Loam textural had high straw, grain and total yield, and high N uptake than other textural groups (Table 2), and the maximum GPC was reached at 80 kg N ha^{-1} (Table 2, Fig. 4A). Moreover, its CMR content was higher at tillering than in other textural groups (Fig. 5A). These results suggest that loam textural group had high available mineral N which decreased test weight and TKW as was previously reported by Bundy and Andraski (2004) on test weight.

Effect of Nitrogen Fertilizer Application Time on Grain Yield, Grain Nitrogen Uptake, Nitrogen Uptake Efficiency, Grain Protein Concentration, and Chlorophyll Meter Readings

Determining the appropriate time to apply N fertilizer at the recommended rate is essential to optimize N management, while maintaining higher wheat yield and quality levels. This study shows that applying N before the point of peak demand permitted an increase in grain yield and grain N uptake compared to the application of the whole amount at sowing (Table 2). In addition, the uptake efficiency was 26 to 29% higher with N120 and N120t treatments compared with N120s (Table 2). Grain protein concentration was higher in N120 and N120t treatments than N120s in L and Sp textural groups and N120 treatment had higher values of GPC in C and Sg textural groups (Table 3). Our results corroborate those of previous studies which reported increased N use efficiency (Grant et al., 1985; Sowers et al., 1994) and higher GPC (Fowler, 2003; López-Bellido et al., 2006) following late top-dressing N fertilization. In all textural groups, higher values of CMR were observed with N120t treatment (Fig. 5). We expected to see higher CMR values with the N120s treatment than with N120t as the former treatment provided the whole amount at sowing and the latter treatment supplied only 50% of the recommended N fertilizer. This shows that it is not efficient to apply the whole amount of N fertilizer at sowing, because N is released when the plants are not fully developed and the unused amount can be lost. Split application of N fertilizer improves the synchronization of N supplied with crop N demand and can help to minimize N losses while increasing N use efficiency. The main challenge is to determine the N fertilizer rate and application time that will maximize yield and minimize losses while ensuring quality yields. It is very important to have a tool that can assess in-season crop N fertilization status (Ortuzar-Iragorri et al., 2005).

Table 3. Summary of ANOVA on the effects of soil texture and N fertilization on grain protein concentration (GPC), thousand kernel weight (TKW), and test weight.

	GPC	TKW	Test weight
	g kg^{-1}	g	kg hL^{-1}
Analysis of variance (*p* value)			
Texture	<0.001	0.008	0.047
Treatment	<0.001	<0.001	0.008
Texture × Treatment	<0.001	<0.001	<0.001
C texture group†			
N120	16.4a‡	29.8b	75.6b
N120s	14.4b	30.9a	76.1a
N120t	14.9b	31.3a	76.6a
L texture group			
N120	15.7a	26.8b	74.0a
N120s	14.5b	27.9a	74.7a
N120t	15.6a	27.7a	74.3a
Sg texture group			
N120	17.6a	28.6a	74.7a
N120s	15.6b	29.3a	74.3a
N120t	16.1b	29.1a	74.2a
Sp texture group			
N120	18.3a	31.1a	76.2a
N120s	16.5b	30.4a	76.2a
N120t	18.0a	30.8a	75.2b

† C: clayey; L: loamy; Sg: sandy, belonging to the Gleysolic soil order; Sp: sandy, belonging to the Podzolic soil order. Textural groups were determined in the 0 to 0.2 m soil layer.

‡ Means followed by the same letter are not statistically significant at 0.05 probability level.

Effect of Nitrogen Fertilizer Rate and Soil Textural Group on Chlorophyll Meter Readings

The CMR approach has the advantage of being faster than tissue or soil testing for N. We found that N fertilizer and soil texture had a significant effect on CMR taken either at tillering or at flowering, and the interaction between fertilization and soil textural group was significant (data not reported). Nitrogen response fertilizer was more on CMR taken at flowering than that taken at tillering (Fig. 5A and 5B). Higher CMR values were observed in C and L compared with the Sg and Sp soil textural groups during both sampling periods (Fig. 5). Chlorophyll meter readings

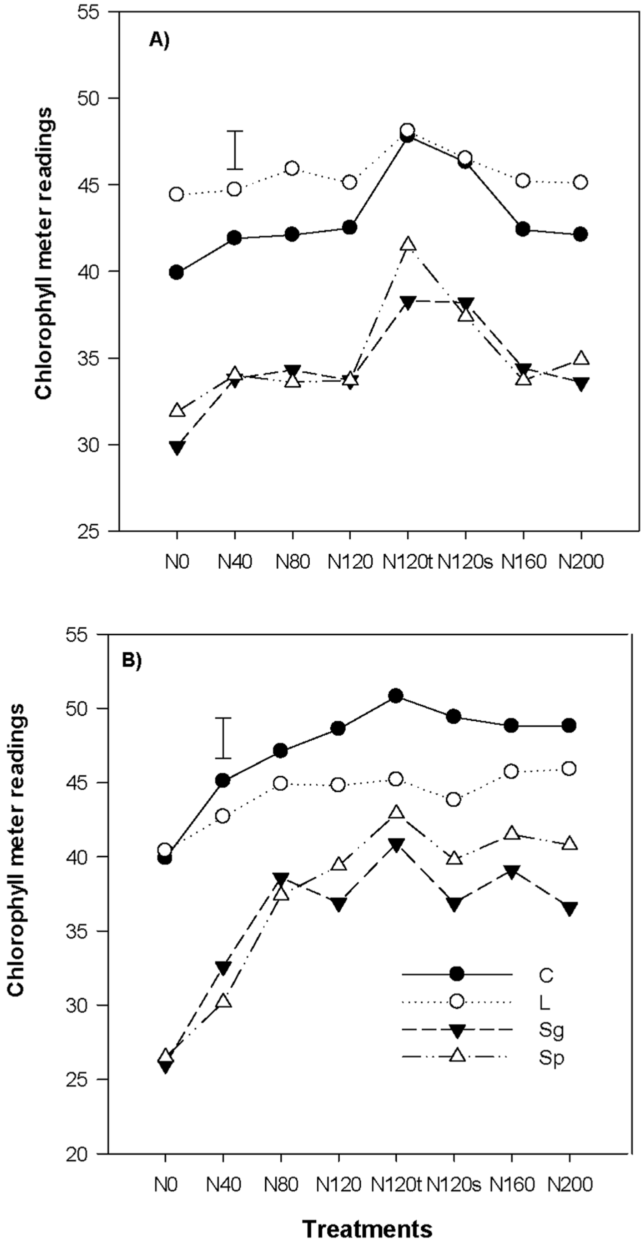

Fig. 5. Influence of soil surface textural groups on chlorophyll meter readings measured (A) at tillering and (B) at flowering. Vertical bars indicate the standard error of the mean. C: clayey; L: loamy; Sg: sandy, belonging to the Gleysolic soil order; Sp: sandy, belonging to the Podzolic soil order. Textural groups were determined in the 0 to 0.2 m soil layer.

ranged from 39.9 to 47.8 in C, from 44.4 to 48.1 in L, from 31.9 to 41.5 in Sp, and from 29.9 to 38.3 in Sg for CMR taken before the second application of N fertilizer (Fig. 5A). Similarly, CMR values ranged from 39.9 to 50.8 in C, from 40.4 to 45.9 in L, from 26.5 to 41.5 in Sp, and from 26 to 40.9 in Sg for CMR taken at flowering (Fig. 5B). Chlorophyll meter readings can be expected to increase as soil N availability increases (Follett et al., 1992). The textural groups C and L had high values of CMR, high straw yield, grain yield, and total yield than sandy soils and yet the total N uptake in all textural groups were comparable (Table 2, Fig. 5). As the biomass produced increases the N concentration decreases by the dilution phenomenon of plant N by C assimilates (Justes et al., 1994), our results imply that sandy soils were associated with higher N concentration than in clay and loam ones (Table 2).

The results from this study indicate that soil surface texture is an important parameter influencing wheat N response and wheat quality parameters. Therefore, the recommended N rate needs to be adjusted taking into account differences in soil surface textures.

Relationship between Chlorophyll Meter Readings and Grain Yield, Total Nitrogen Uptake, and Grain Protein Content

It would be advantageous to obtain chlorophyll meter readings at an early growth stage when the crop can still respond to top-dressed N fertilizer (Follett et al., 1992). In this study, the first CMR was taken before the second application of N fertilizer at tillering and the second one at flowering. Relative CMR values which were calculated as the ratio between treatment mean CMR and the highest mean CMR were correlated with grain yield, N uptake, and GPC. In all cases, a positive relationship was found between the relative CMR and the dependent variables, and relative CMR taken at flowering explained higher variation of grain yield, N uptake, and GPC than those taken at tillering (Fig. 6). The variation in wheat yield, N uptake and GPC explained by the relative CMR taken at tillering was 74, 19, and 6%, whereas it was of 87%, 88%, and 73% for the relative CMR taken at flowering (Fig. 6). A timely sidedress N application need to be performed before the period of peak demand and flowering marks the beginning of the high N demand period when most of N taken up by wheat is allocated directly to the grains. Therefore, unless air-system is used, applying N fertilizer at flowering is too late for many regions of the world including Québec. The fact that a high variation of GY, GPC, and total N uptake was explained by CMR at flowering means that this tool can provide useful information on N nutrition status during the growing season, and can serve as a report-card test to adjust fertilizer N rate in the following growing season. Our results corroborate those reported previously by Follett et al. (1992) and Spaner et al. (2005), in which a positive correlation was found between CMR and wheat yield and/or GPC. Peltonen et al. (1995) reported that CMR provided a better estimate of potential yield than leaf N concentration. Wheat yield increased by 20% when 30 kg N ha^{-1} was applied at CMR <42 at maximum tillering (Singh et al., 2002), and Follett et al. (1992) reported that a yield response in wheat is expected when CMR <42 at the late tillering stage. To be useful, CMR must be calibrated, since the readings depend on many factors such as crop variety, stage of growth, crop diseases, location, and cultural practices (Follett et al., 1992). In addition, timing of N fertilization can also confound calibration and make interpretation difficult (Schepers et al., 1992).

It is important to mention that wheat response to N fertilizer and soil textural group observed in this study was influenced by year-to-year changes in environmental conditions associated with rainfall pattern and air temperature, and soil water content. Previous studies have reported that wheat grain-filling process is influenced by water availability (Zhang and Oweis, 1999; Calvino et al., 2003) and temperature (Hatfield et al., 2011). For instance, heavy rainfall observed in early spring of 2006 compared to other years (Fig. 1) could have caused anoxia, root disease, and increased compaction in fine-textured soils. Eghball and Varvel (1997) reported that seasonal weather conditions can exert a greater influence on soil N dynamics and crop N response than soil properties

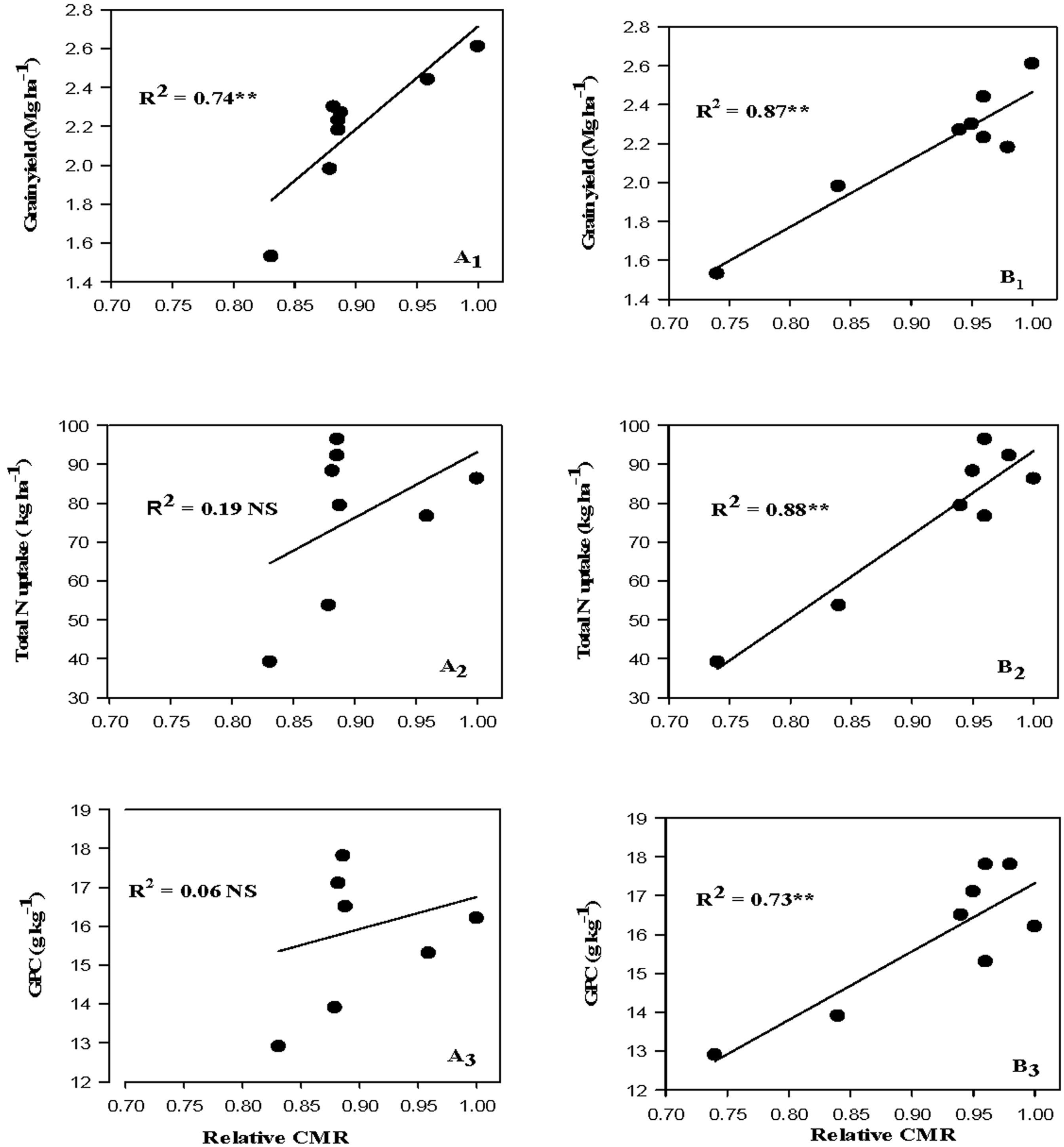

Fig. 6. Relationships between relative chlorophyll meter readings measured at tillering (A_1, A_2, A_3) and at flowering (B_1, B_2, B_3) and wheat grain yield, N uptake, and grain protein concentration (GPC). Relative chlorophyll meter reading (CMR) were calculated as the ratio between treatment mean CMR and the highest mean CMR. Data points represent treatments averaged over site-years. NS, not significant; **, significant at 0.01 probability level.

and landscape attributes. Therefore, different results could be expected in an environment different to ours.

CONCLUSIONS

Results from this study demonstrated that total N uptake increased proportionally to the N fertilizer rate applied, up to a level of 200 kg N ha^{-1} and GPC followed similar trend in C and Sp textural groups. However, the lowest N efficiency was found at an application rate of 200 kg N ha^{-1}. Applying half of the recommended N rate (120 kg ha^{-1}) at planting and the rest at tillering permitted the attainment of a high yield, high grain N uptake and the highest CMR and this corresponds to the currently recommended N rate for wheat in Québec. The effect of N fertilizer rate was significant on almost all parameters, that of surface soil texture was significant on total yield, total N uptake, and their interaction was significant on GPC, TKW, test weight, and CMR. The results indicate that surface soil texture is an important parameter that influences wheat N response and wheat quality parameters.

Chlorophyll meter readings taken at flowering is a good way to diagnose in-season wheat N nutrition, because they explained up to 88% of the variation in wheat yield, N uptake, and GPC. At the studied sites, applying more than 120 kg N ha^{-1} for spring wheat was not beneficial for wheat productivity or quality and wheat N response was affected by soil texture and this factor need to be considered in N fertilizer recommendation.

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REFERENCES

Bird, M.I., E.M. Veenendaal, C. Moyo, J. Lloy, and P. Frost. 2000. Effect of fire and soil texture on soil carbon in a subhumid savanna (Matopos, Zimbabwe). Geoderma 94:71–90. doi:10.1016/S0016-7061(99)00084-1

Bundy, L.G., and T.W. Andraski. 2004. Diagnostic tests for site-specific nitrogen recommendation for winter wheat. Agron. J. 96:608–614. doi:10.2134/agronj2004.0608

Calvino, P.A., F.H. Andrade, and V.O. Sadras. 2003. Maize yield as affected by water availability, soil depth, and crop management. Agron. J. 95:275–281. doi:10.2134/agronj2003.0275

Cambouris, A.N., M.C. Nolin, B.J. Zebarth, and M.R. Laverdière. 2006. Soil management zones delineated by electrical conductivity to characterize spatial and temporal variations in potato yield and in soil properties. Am. J. Potato Res. 83:381–395. doi:10.1007/BF02872015

Campbell, C.A., F. Selles, R.P. Zentner, B.J. McConkey, S.A. Brandts, and R.C. McKenzie. 1997. Regression model for predicting yield of hard red spring wheat grown on stubble in the semiarid prairie. Can. J. Plant Sci. 77:43–52. doi:10.4141/P96-043

Canadian Grain Commission board. 2011. Grain quality. Wheat methods and test used to measure quality. Gov. of Canada, Canadian Grain Commission Headquarters, Winnipeg, MB. http://www.grainscanada.gc.ca/wheat-ble/method-methode/wmtm-mmab-eng.htm (accessed 18 Aug. 2011).

Carr, P.M., G.B. Martin, and R.D. Horsley. 2008. Wheat grain quality response to tillage and rotation with field pea. Agron. J. 100:1594–1599. doi:10.2134/agronj2008.0122

Cox, M.S., P.D. Gerard, M.C. Wardlaw, and M.J. Abshire. 2003. Variability of selected soil properties and their relationships with soybean yield. Soil Sci. Soc. Am. J. 67:1296–1302. doi:10.2136/sssaj2003.1296

CRAAQ. 2003. Fertilization reference guide. Centre de reference en agriculture et agroalimentaire du Québec, Ste-Foy, QC, Canada. (In French.)

CRAAQ. 2010. Guide de référence en fertilisation. 2nd ed. Centre de référence en agriculture et agroalimentaire du Quebec, Ste-Foy, QC, Canada. (In French.)

Delogu, G., L. Cattivelli, N. Pecchioni, D. De Falcis, T. Maggiore, and A.M. Stanca. 1998. Uptake and agronomic efficiency of nitrogen in winter barley and winter wheat. Eur. J. Agron. 9:11–20. doi:10.1016/S1161-0301(98)00019-7

Eghball, B., and G.E. Varvel. 1997. Fractal analysis of temporal yield variability of crop sequences: Implications for site-specific management. Agron. J. 89:851–855. doi:10.2134/agronj1997.00021962008900060001x

Fageria, N.K., and V.C. Baligar. 2005. Enhancing nitrogen use efficiency in crop plants. Adv. Agron. 88:97–185. doi:10.1016/S0065-2113(05)88004-6

Flaten, D.N., and G.J. Racz. 1997. Nitrogen fertility and protein in red spring wheat. In: Proceedings of Manitoba Agri-Forum 97, Winnipeg, MB, Canada. 18 Feb. 1997. Manitoba Agric. Food and Rural Initiatives, Winnipeg, MB. p. 72–75.

Follett, R.H., R.F. Follett, and A.D. Halvorson. 1992. Use of chlorophyll meter to evaluate the nitrogen status of dryland winter wheat. Commun. Soil Sci. Plant Anal. 23:687–697. doi:10.1080/00103629209368619

Fowler, D.B. 2003. Crop nitrogen demand and grain protein concentration of spring winter wheat. Agron. J. 95:260–265. doi:10.2134/agronj2003.0260

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1996. Active fractions of organic matter in soils with different texture. Soil Biol. Biochem. 28:1367–1372. doi:10.1016/S0038-0717(96)00143-5

Gagnon, B., and N. Ziadi. 2010. Grain corn and soil nitrogen responses to sidedress nitrogen sources and application. Agron. J. 102:1014–1022. doi:10.2134/agronj2010.0011

Grant, C.A., E.H. Stobbe, and G.J. Racz. 1985. The effect of fall-applied N and P fertilizer and timing of N application on yield and protein content of winter wheat grown on zero-tilled land in Manitoba. Can. J. Soil Sci. 65:621–628. doi:10.4141/cjss85-068

Hassink, J. 1994. Effect of soil texture and grassland management on soil organic C and N rates of C and N mineralization. Soil Biol. Biochem. 26:1221–1231. doi:10.1016/0038-0717(94)90147-3

Hatfield, J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, and D. Wolfe. 2011. Climate impacts on agriculture implications for crop production. Agron. J. 103:351–370.

Hendershot, W.H., H. Lalande, and M. Duquette. 1993a. Soil reaction and exchangeable acidity. In: M.R. Carter, editor, Soil sampling and methods of analysis. Lewis Publ., Boca Raton, FL. p. 141–146.

Hendershot, W.H., H. Lalande, and M. Duquette. 1993b. Ion exchange and exchangeable cations. In: M.R. Carter, editor, Soil sampling and methods of analysis. Lewis Publ., Boca Raton, FL. p. 167–176.

Hook, S.C.W. 1984. Specific weight and wheat quality. J. Sci. Food Agric. 35:1136–1141. doi:10.1002/jsfa.2740351013

Isaac, R.A., and W.C. Johnson. 1976. Determination of total nitrogen in plant tissue using a block digestor. J. Assoc. Off. Anal. Chem. 59:98–100.

Justes, E., B. Mary, J.-M. Meynard, J.-M. Machet, and L. Thelier-Huches. 1994. Determination of a critical nitrogen dilution curve for winter wheat crops. Ann. Bot. (London) 74:397–407. doi:10.1006/anbo.1994.1133

Karamanos, R.E., N.A. Flore, and J.T. Harapiak. 2005. Effect of post emergence nitrogen application on the yield and protein content of wheat. Can. J. Plant Sci. 85:327–342. doi:10.4141/P04-091

Kleijer, G., L. Levy, R. Schwaerzei, D. Fossat, and C. Brabant. 2007. Relationship between test weight and several quality parameters in wheat. Revue Suisse Agric. 39:305–309.

Lamontagne, L., and M.C. Nolin. 1997. Dossier des noms de sols du Québec 1997. Contribution no. 971124. Agriculture and Agri-Food Canada, Quebec QC, Canada. (In French.)

Leclerc, M.L., M.C. Nolin, D. Cluis, and R.R. Simard. 2001. Grouping soils of Montreal lowlands (Quebec) according to fertility and P sorption and desorption characteristics. Can. J. Soil Sci. 81:71–83. doi:10.4141/S00-021

Lehane, J.J., and W.J. Staple. 1965. Influence of soil texture, depth of soil moisture storage, and rainfall distribution on wheat yields in southwestern Saskatchewan. Can. J. Soil Sci. 45:207–219. doi:10.4141/cjss65-029

López-Bellido, L., R.J. López-Bellido, and F.J. López-Bellido. 2006. Fertilizer nitrogen efficiency in durum wheat under rainfed Mediterranean conditions: Effects of split applications. Agron. J. 98:55–62. doi:10.2134/agronj2005.0017

Lukow, O.M., and P.B.E. McVetty. 1991. Effect of cultivar and environment on quality characteristics of spring wheat. Cereal Chem. 68:597–601.

Manning, G., L.G. Fuller, D.N. Flaten, and G. Eilers. 2001. Wheat yield and grain protein variation within an undulating soil landscape. Can. J. Soil Sci. 81:459–467. doi:10.4141/S00-059

McConkey, B.G., C.A. Campbell, R.P. Zentner, F.B. Dyck, and F. Selles. 1996. Long-term tillage effects on spring wheat production on three soil textures in the Brown soil zone. Can. J. Plant Sci. 76:747–756. doi:10.4141/cjps96-127

McKenzie, R.H., R. Andreuik, and M. McLelland. 2008. High protein wheat production. Alberta agriculture and rural development department. Gov. of Alberta, Alberta Agric. and Rural Development Department. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex95 (accessed 18 Aug. 2011).

McKenzie, R.H., E. Bremer, C.A. Grant, A.M. Johnston, J. DeMulder, and A.B. Middleton. 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. doi:10.4141/S05-026

Melaj, M.A., H.E. Echeverría, S.C. López, G. Studdert, F. Andrade, and N.O. Bárbaro. 2003. Timing of nitrogen fertilization in wheat under conventional and no-tillage system. Agron. J. 95:1525–1531. doi:10.2134/agronj2003.1525

Nolin, M.C., C. Wang, and M.J. Caillier. 1989. Fertility grouping of Montreal lowlands soil mapping units based on selected soil characteristics of the plow layer. Can. J. Soil Sci. 69:525–541. doi:10.4141/cjss89-054

Nyiraneza, J., M.H. Chantigny, A. N'Dayegamiye, and M.R. Laverdière. 2010. Long-term manure application and forage reduce nitrogen fertilizer requirements of silage-corn cereal cropping systems. Agron. J. 102:1244–1251. doi:10.2134/agronj2009.0480

Oberle, S.L., and D.R. Keeney. 1990. Factors influencing corn fertilizer N requirements in the Northern U.S. Corn Belt. J. Prod. Agric. 3:527–534.

Ortuzar-Iragorri, M.A., A. Alonso, A. Castellón, G. Besga, G. Estavillo, and A. Aizpurua. 2005. N-tester use in soft winter wheat: Evaluation of nitrogen status and grain yield prediction. Agron. J. 97:1380–1389. doi:10.2134/agronj2004.0268

Palta, J.A., and L.R. Fillery. 1993. Postanthesis remobilization and losses of nitrogen in relation to applied nitrogen. Plant Soil 155-156:179–191. doi:10.1007/BF00025013

Peltonen, J., A. Virtanen, and E. Haggrèn. 1995. Using a chlorophyll meter to optimize nitrogen fertilizer application for intensively-managed small-grain cereals. J. Agron. Crop Sci. 174:309–318. doi:10.1111/j.1439-037X.1995.tb01118.x

Peng, S., F.V. García, R.C. Laza, and K.G. Cassman. 1993. Adjustment for specific leaf weight improves chlorophyll meter's estimate of rice leaf nitrogen concentration. Agron. J. 85:987–990. doi:10.2134/agronj1993.00021962008500050005x

SAS Institute. 2004. SAS Online Doc. Version 9.1.3. SAS Inst., Cary, NC.

Schepers, J.S., D.D. Francis, M. Vigil, and F.E. Below. 1992. Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. Commun. Soil Sci. Plant Anal. 23:2173–2187. doi:10.1080/00103629209368733

Schuler, S.F., R.K. Bacon, P.L. Finney, and E.E. Gbur. 1995. Relationship of test weight and kernel properties to milling and baking quality in soft red winter wheat. Crop Sci. 35:949–953. doi:10.2135/cropsci1995.0011183X003500040001x

Schuler, S.F., R.K. Bacon, and E.E. Gbur. 1994. Kernel and spike character influence on test weight of soft red winter wheat. Crop Sci. 34:1309–1313. doi:10.2135/cropsci1994.0011183X003400050031x

Sheldrick, B.H., and C. Wang. 1993. Particle size distribution. In: M.R. Carter, editor, Soil sampling and methods of analysis. Lewis Publ., Boca Raton, FL. p. 499–511.

Singh, B., Y. Singh, J.K. Ladha, K.F. Bronson, V. Balasubramanian, J. Singh, and C.S. Khind. 2002. Chlorophyll meter and leaf color chart-based nitrogen management for rice and wheat in northwestern India. Agron. J. 94:821–829. doi:10.2134/agronj2002.0821

Spaner, D., A.G. Todd, A. Navabi, D.B. McKenzie, and L.A. Goonewardene. 2005. Can leaf chlorophyll measures at different growth stages be used as an indicator of winter wheat and spring barley requirements in eastern Canada? J. Agron. Crop Sci. 191:393–399. doi:10.1111/j.1439-037X.2005.00175.x

Sowers, K.E., W.L. Pan, B.C. Miller, and J.L. Smith. 1994. Nitrogen use efficiency of split nitrogen applications in soft winter wheat. Agron. J. 86:942–948. doi:10.2134/agronj1994.00021962008600060004x

Tiessen, H., and J.O. Moir. 1993. Total and organic carbon. In: M.R. Carter, editor, Soil sampling and methods of analysis. Lewis Publ., Boca Raton, FL. p. 187–199.

Tiessen, K.H.D., D.N. Flaten, C.A. Grant, R.E. Karamanos, and M.H. Entz. 2005. Efficiency of fall-banded urea for spring wheat production in Manitoba: Influence of application date, landscape position and fertilizer additives. Can. J. Soil Sci. 85:649–666. doi:10.4141/S05-017

Tran, T.S., and G. Tremblay. 2000. Recovery of 15N-labeled fertilizer by spring bread wheat at different N rates and application times. Can. J. Soil Sci. 80:533–539. doi:10.4141/S99-098

USDA. 1977. The official United States standards for grain. USDA Fed Grain Insp. Ser., U.S. Gov. Print Office, Washington, DC.

Wienhold, B.J., and J.M. Krupinsky. 1999. Chlorophyll meter as a nitrogen management tool in malting barley. Commun. Soil Sci. Plant Anal. 30:2551–2562. doi:10.1080/00103629909370394

Yang, Y.C., M. Zhang, L. Zheng, D.D. Cheng, M. Liu, and Y.Q. Geng. 2011. Controlled-release urea improved nitrogen use efficiency, yield and quality of wheat. Agron. J. 103:479–485.

Zhang, P., and T. Oweis. 1999. Water yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agric. Water Manage. 38:195–211. doi:10.1016/S0378-3774(98)00069-9

Ziadi, N., G. Bélanger, A. Claessens, L. Lefebvre, N. Tremblay, A.N. Cambouris, M.C. Nolin, and L.E. Parent. 2010. Plant-based diagnostic tools for evaluating wheat N status. Crop Sci. 50:2580–2590. doi:10.2135/cropsci2010.01.0032

Ziadi, N., C.A. Grant, N. Samson, J. Nyiraneza, G. Bélanger, and L.E. Parent. 2011. Efficiency of controlled-release urea for a potato production system in Québec, Canada. Agron. J. 103:60–66. doi:10.2134/agronj2010.0298

Zvomuya, F., C.J. Rosen, M.P. Russelle, and S.C. Gupta. 2003. Nitrate leaching and nitrogen recovery following application of polyolefin-coated urea to potato. J. Environ. Qual. 32:480–489. doi:10.2134/jeq2003.0480