Use of Grain Protein Concentration as an Indicator of N Deficiency in Spring and Winter Wheat

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Abstract

Available soil N and a cultivars genetic potential are the primary factors determining grain protein concentration (GPC). Several studies have suggested that the close relationship between GPC and the amount of available soil N may allow GPC to be used as a post harvest indicator of growing season soil N deficiencies. The objective of this study was to determine if GPC was a practical indicator of crop N deficiencies in a wide range of wheat cultivars grown under the variable environmental conditions of western Canada. Wheat cultivars and lines representing quality types and GPC ranging from low protein soft white through Canada Prairie Spring and hard red winter to high protein hard red spring were grown in a total of 16 N fertilizer trials on dryland at Saskatoon, Clair and Yorkton and partial irrigation at Saskatoon from 1992 to 1998. Two methods were used to determine GPC at maximum grain yield and 90 and 80 percent of maximum grain yield. Both genotype and environment influenced the upper limit of yield when N was not limiting. While variation amongst cultivars tended to be smaller within market classes, it was large enough to suggest that the critical GPC-grain yield responses must be know for each cultivar before GPC can be used as a practical post-harvest indicator of N sufficiency. Growing season weather conditions also had a large influence on GPC-grain yield relationships and as the potential grain yield of a cultivar was reduced by environmental limitations the GPC at the point of maximum grain yield increased. Similar GPC-grain yield relationships were found at 90 and 80 percent of maximum grain yield. These observations indicate that GPC may be a useful post - harvest indicator of N deficiencies for crops that are under high N stress but caution must be used when employing GPC to develop management systems that optimize N fertilizer use.

Introduction

Nitrogen (N) is the basic building block of protein. N uptake by a plant is dependent upon a substrate inducible, relatively unstable enzyme, nitrate reductase, which is regulated by the level of available soil N (Eilrich and Hageman 1973). It has been suggested that this relationship may allow grain protein concentration (GPC) to be used as post-harvest indicator of the adequacy of N management (Grant and Flaten, 1998). For example, the N requirements for maximum grain yield are normally met when the GPC - N response curve for Norstar winter reaches approximately 13 % under average to good weather conditions in Saskatchewan (Fowler and Brydon, 1989). Similarly, the critical GPC for spring wheat has been reported as 13.5 % for both the eastern prairies (Flaten and Racz, 1997) and Montana (Long and Engel, 1998). Selles and Zentner (2001) reported a grain protein concentration of 12.8 % was a reliable indicator of N sufficiency in hard red spring wheat grown in south eastern Saskatchewan. However, it has been noted that there are important differences in threshold GPC that are dependent on cereal species and cultivars within species (Fowler et al., 1990). Consequently, the objectives of this study were to investigate the relationships between GPC and grain yield for cultivars and lines representing the western Canadian wheat quality classes grown under a range of environmental conditions to determine if GPC has wide application as an indicator of crop N deficiencies.

Materials and Methods

A total of 16 fertilizer trials consisting of five spring and five winter wheat cultivars representing quality types and GPC ranging from low protein soft white through Canada Prairie Spring (CPS) and hard red winter (HRW) to high protein hard red spring (HRS) were grown on dryland at Saskatoon, Clair and Yorkton and partial irrigation at Saskatoon from 1992 to 1998. Cultivars were selected to represent the most highly adapted cultivars for these classes and this region. Additional data and new releases resulted in several cultivar changes over the course of this study.

Trials that included spring wheat were grown under partial irrigation at Saskatoon in 1992, 1993, 1994, 1995, 1996, 1997, and 1998, on dryland at Saskatoon in 1996 and 1997 and Clair in 1996, 1997, and 1998. Trials that included winter wheat were grown under partial irrigation at Saskatoon in 1993, 1995, 1997, and 1998, and on dryland at Saskatoon in 1997, Yorkton in 1997 and 1998 and at two locations at Clair in 1997. The cultivars AC Reed, Katepwa, BW90, Roblin and AC Taber were included in the spring wheat trials starting in 1992. Glenlea replaced BW90 in 1995, AC Barrie was substituted for Roblin in 1997, and AC Vista replaced AC Reed in 1998. CDC Ptarmigan, CDC Kestrel, S86-101, Norstar, and Winalta were included in all winter wheat trials up to 1996 and in Saskatoon and Clair dryland trials in 1997. The winter wheat cultivars CDC Kestrel, CDC Clair, and CDC Osprey were grown in trials under partial irrigation at Saskatoon and dryland at Clair and Yorkton in 1997. The 1998 winter wheat cultivars were Norstar, Winalta, CDC Harrier, CDC Osprey, and CDC Clair.

All trials were direct-seeded into standing stubble from a previous crop (no-till) with a small plot hoe-press drill. Each plot was 5.5 m long and 1.2 m wide. Optimum seeding dates were achieved in all trials and phosphate fertilizer was applied with the seed at recommended rates. Nitrogen fertilizer was added as early spring broadcast ammonium nitrate (34-0-0) at 0, 40, 80, 120, 160 and 240 kg N/ha. Other elements were not considered limiting. Experimental design was a 4-replicate split-plot with N fertilizer rates as the main plots and cultivars as the sub-plots.

Grain protein concentrations were determined for each plot in each trial. Protein concentrations were determined from Kjeldahl N (N x 5.7), Leco N, or the near-infrared spectroscopy method (13.5 % w/w m.b.). Leco analyses were utilized to standardize GPC in each trial analyzed by the near-infrared spectroscopy method. Winter wheat grain yields are also reported at 13.5 % moisture.

Analyses of variance were conducted to determine the level of significance of differences due to trials, N response, and cultivar and the interactions among the main effects. Regression analyses of treatment means were used to plot curves that best described the shape and behavior of the grain yield and GPC - N fertilizer responses. The peak four-parameter Weibull equation was employed to describe the grain yield response and the sigmoidal four-parameter Gompertz equation was used to describe the GPC response to N fertilizer applications (Fig. 1). The peak three-parameter log normal equation was also used to describe the relationship between grain yield and GPC using the individual plot data for each cultivar at each location (Fig. 2). Nonlinear regression procedures outlined by SigmaPlot (SPSS Inc., Chicago, IL, USA) were used to provide least squares estimates of the regression coefficients in these equations.

Two methods were employed to identify critical grain yield - GPC relationships. A) Maximum grain yield (Ymax) and the N rates required to achieve Ymax and 90 and 80 % of Ymax were estimated using the peak four-parameter Weibull equation. These N rates were then the used to estimate the GPC at maximum grain yield (Pmax) and 90 (P90) and 80 (P80) % of Ymax using the sigmoidal four-parameter Gompertz equation (Fig. 1). B) GPC at maximum grain yield and 90 an 80 % of maximum grain yield were also estimated using the peak three-parameter log normal equation (Fig. 2). Because this study was only concerned with GPC at grain yields that were 80 % or more of the maximum, initial decreases in GPC - N responses at low levels of applied N were disregarded to increase the accuracy and simplify curve fitting (Fig. 1 and 2). Estimates of maximum and 90 and 80 % of maximum grain yield and GPC at maximum grain yield and 90 and 80 % of maximum grain for each cultivar in each trial were then subjected to analysis of variance using the General Linear Model procedure of Minitab 13 (Minitab Inc., State College, PA). Adjusted means for these variables are reported.

Results and Discussion

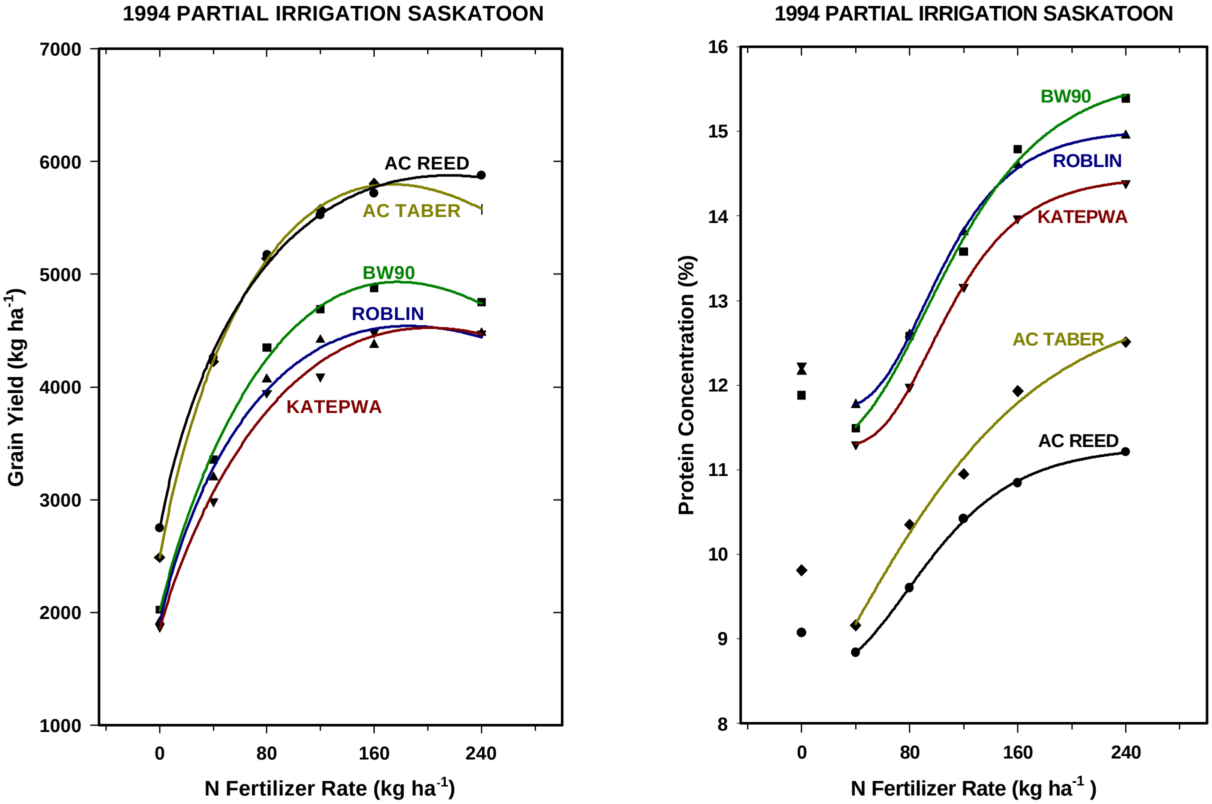

Figure 1. Grain yield and GPC response to nitrogen fertilizer for five spring wheat genotypes grown under partial irrigation at Saskatoon in 1994. The peak four-parameter Weibull equation was employed to describe the grain yield response and the sigmoidal four-parameter Gompertz equation was used to describe the GPC response to N fertilizer applications.

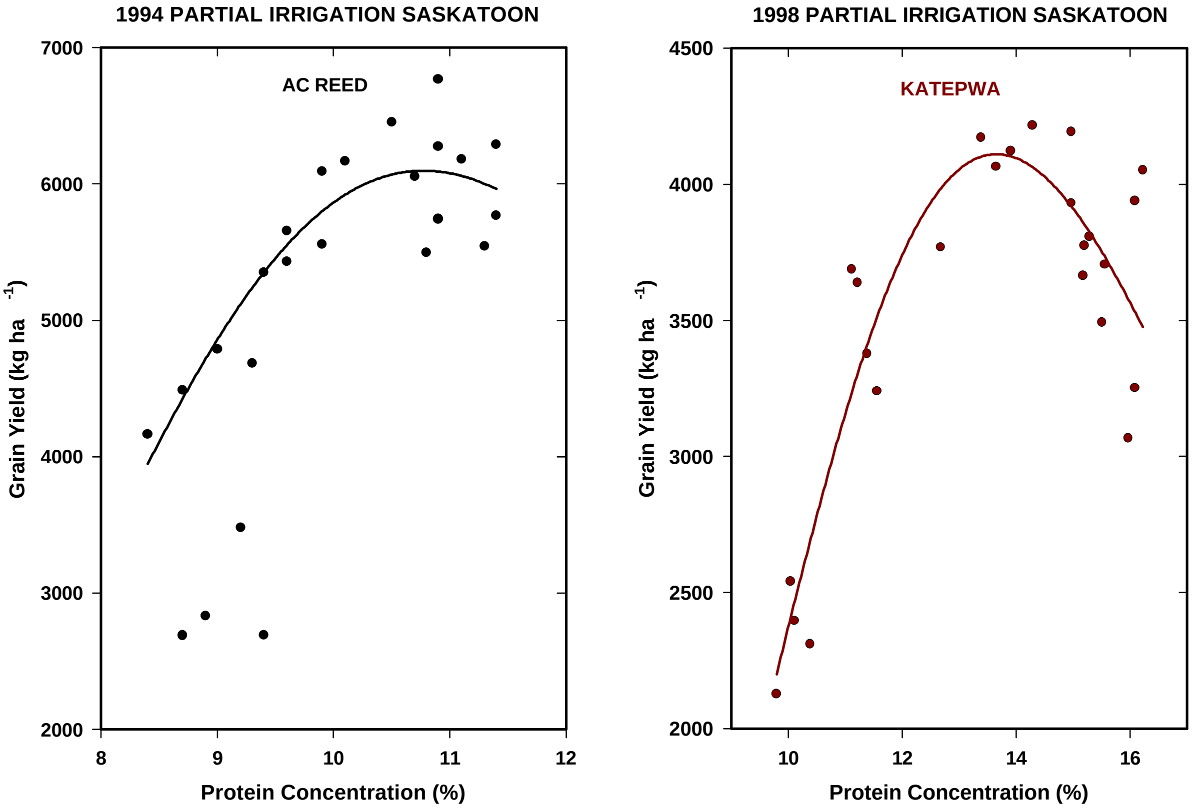

Figure 2. Relationships between grain yield and GPC for AC Reed and Katepwa grown under partial irrigation at Saskatoon in 1994 and 1998 respectively. GPC at maximum grain yield and 90 an 80 % of maximum grain yield were estimated using the peak three-parameter log normal equation (Table 2).

The fields in which these trials were grown had low levels of residual N. Deficiencies in plant available N combined with conditions for growth that were average to excellent produced large crop responses to added N. Analysis of variance for grain yield and GPC indicated that differences due to cultivars and rate of N fertilizer application were significant ($P<0.05$) for all trials. Nitrogen fertilization was responsible for the largest proportion of the variability in GPC (Fowler, 1998b) and large GPC responses were accompanied by increases in grain yield that often more than doubled in response to the first 120 kg ha^{-1} fertilizer N.

The peak four-parameter Weibull equation was employed to describe the grain yield response and the sigmoidal four-parameter Gompertz equation was used to describe the GPC response to N fertilizer applications (examples given in Fig. 1) for the 99 genotype/trial comparisons made in this study. Average reductions in sums of squares due to model were 97.5 and 98.9 %, respectively, indicating that these equations provided an excellent fit to the observed data. Maximum grain yields (Ymax) and the N rates required to achieve Ymax and 90 and 80 % of Ymax were also estimated using the peak four-parameter Weibull equation. These N rates were then used to estimate the protein concentration at maximum grain yield (Pmax) and 90 (P90) and 80 (P80) % of Ymax using the sigmoidal four-parameter Gompertz equation (Table 1). GPC at maximum grain yield and 90 an 80 % of maximum grain yield were also estimated by fitting the grain yield and GPC data for each of the 99 genotype/trial comparisons to the peak three-parameter log normal equation (examples given in Fig. 2). In this instance, average reduction in sums of squares due to model was 65.6 %. The two approaches (Fig. 1 and 2) used the same database and arrived at similar estimates of maximum grain yield and GPC at maximum grain yield and 90 an 80 % of maximum grain yield (Table 1 and 2).

Table 1. Number of trials and maximum grain yields (Ymax) and protein concentrations at maximum grain yield (Pmax) and 90 (P90) and 80 (P80) % of maximum grain yield for eight spring and seven winter wheat genotypes. Grain yields were estimated using the peak four-parameter Weibull equation and protein concentrations were estimated the using the sigmoidal four-parameter Gompertz equation (see Fig. 1).

Genotype	**Market Class**	**Number of Trials**	**Ymax** (kg ha^{-1})	**Pmax** (%)	**P90** (%)	**P80** (%)
Spring Wheat						
Katepwa	HRS[Z]	12	3906	14.9	12.5	11.6
Roblin	HRS	7	4073	15.4	13.3	12.2
AC Barrie	HRS	5	4111	15.9	13.6	12.4
Glenlea	ESS	9	4344	14.0	11.4	10.7
BW90	HRS	3	4419	15.5	13.9	13.2
AC Taber	CPSR	12	5257	12.5	10.6	10.0
AC Reed	SWS	10	5317	11.4	9.8	9.2
AC Vista	CPSW	2	5589	12.7	10.4	9.4
Winter Wheat						
Winalta	HRW	6	4580	13.4	11.7	10.8
S86-101	HRW	4	5140	12.2	10.4	9.6
Norstar	HRW	6	5232	12.2	10.4	9.5
CDC Harrier	HRW	2	5310	12.0	10.6	9.7
CDC Osprey	HRW	5	5344	13.3	12.0	10.8
CDC Kestrel	HRW	7	5507	11.6	10.2	9.4
CDC Clair	HRW	5	5589	13.1	11.9	10.8
CDC Ptarmigan	SWW	4	5844	10.7	8.9	8.4
SD[y]			356	0.42	0.55	0.62

[Z] **HRS** - Hard Red Spring, **ESS** - Extra Strong Spring, **CPSR** - Canadian Prairie Spring red, **CPSW** - Canadian Prairie Spring White, **SWS** - Soft White Spring, **HRW** - Hard Red Winter, **SWW** - Soft White Winter. Note: BW90 and S86-101 are not registered cultivars. [y] SD - Standard Deviation.

The typical GPC - N response pattern (Fowler 1998a), which includes the three phases designated as zones of minimum percentage, poverty adjustment, and luxury consumption described by Macy (1936), were observed in these trials (Fig. 1). Low GPC were associated with low residual soil - available N levels and favourable growing conditions. In these instances, N fertilization stimulated large increases in both grain yield and grain protein yield that produced a **lag phase** (zone of minimum percentage) in the GPC - N response curve. The lag phase was longest when cultivars with a high grain yield potential were grown under low levels of available soil N. Under these conditions, the correction of severe N stress by the addition of fertilizer N often produced an initial decrease in the GPC - N response curve that extended beyond the 50 kg ha^{-1} N level (Fowler et al., 1989). The lag phase of the GPC response curve became shorter as environmental limitations increased or cultivar grain yield potential decreased and it often disappeared entirely at higher levels of residual soil available N.

Once cultivar yield potential or environmental factors other than available N become limiting to plant growth, excess N was utilized mainly for grain protein production and the GPC - N response curve entered an **increase phase (**zone of poverty adjustment). During this phase, GPC increased rapidly, even under favourable growing conditions. However, the response curve turned up at lower N levels and tailed off at higher GPC under poor compared to good growing conditions.

The GPC response to increased N quickly diminished to near zero when cultivar yield potential or environmental factors, such as moisture, limited grain yield. The end of the increase phase and the start of the **maximum phase** (zone of luxury consumption) of the GPC - N response curve usually occurred at approximately the same N rate as maximum grain yield was achieved. A detrimental effect that resulted in yield depression was observed at high N levels.

Both genotype (Table 1 and 2) and environment influenced the upper limit of yield when N was not limiting. Maximum grain yields ranged from an average of 4140 kg ha^{-1} on dryland at Saskatoon in 1998 to 6767 kg ha^{-1} under partial irrigation at Saskatoon in 1992 for spring wheat and from 2793 kg ha^{-1} under dryland at Yorkton in 1997 to 6457 kg ha^{-1} under partial irrigation at Saskatoon in 1993 for winter wheat. The cultivars in these studies represented the western Canadian wheat market classes, which in turn represent the extremes in grain yield and protein concentration. For example, average protein concentration ranged from 10.7 % for CDC Ptarmigan to 15.5 % for BW90 at maximum grain yield while Katepwa had a maximum grain yield that was only 67 % of CDC Ptarmigan (Table 1).

Table 2. Number of trials and maximum grain yields (Ymax) and protein concentrations at maximum grain yield (Pmax) and 90 (P90) and 80 (P80) % of maximum grain yield for eight spring and seven winter wheat genotypes. Grain yields and protein concentrations were estimated the using the peak three-parameter log normal equation (see Fig. 2).

Genotype	**Number of Trials**	**Ymax** (kg ha^{-1})	**Pmax** (%)	**P90** (%)	**P80** (%)
Spring Wheat					
Katepwa	12	3855	14.1	12.1	11.3
Roblin	7	4068	15.4	13.0	12.1
AC Barrie	5	4125	14.7	12.7	11.9
Glenlea	9	4301	13.4	11.1	10.2
BW90	3	4240	15.7	14.0	13.3
AC Taber	12	5221	12.2	10.4	9.7
AC Reed	10	5321	11.1	9.7	9.0
AC Vista	2	5620	12.4	10.4	9.5
Winter Wheat					
Winalta	6	4528	13.1	11.4	11.0
S86-101	4	5163	11.4	9.9	9.3
Norstar	6	5110	11.9	10.1	9.5
CDC Harrier	2	5169	11.9	10.1	9.6
CDC Osprey	5	5161	12.8	11.1	10.6
CDC Kestrel	7	5371	11.2	9.7	9.2
CDC Clair	5	5399	12.9	11.5	10.9
CDC Ptarmigan	4	5815	10.2	8.9	8.3
SD		329	0.58	0.81	0.72

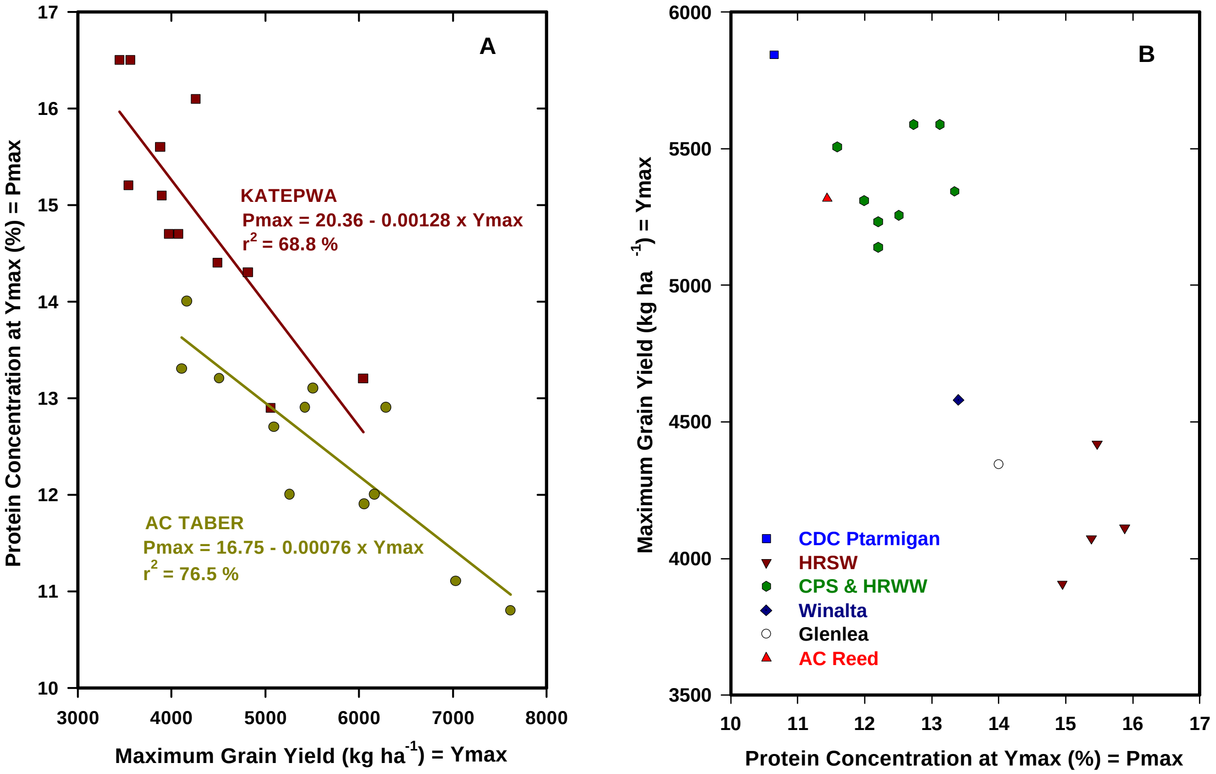

Figure 3. A. The relationship between environmental maximum grain yield (Ymax) and protein concentration (Pmax) for Katepwa and AC Taber spring wheat grown in 12 N fertilizer trials. Ymax and Pmax were estimated using the peak four-parameter Weibull equation and the sigmoidal four-parameter Gompertz equation, respectively. B. The relationship between maximum grain yield (Ymax) and protein concentration (Pmax) for spring and winter wheat genotypes. See Table 1 for means.

As the maximum potential grain yield of a genotype was reduced by environmental factors, which in this case was primarily water availability, the protein concentration at the point of maximum grain yield increased (Fig. 3A). The results of this study also revealed that there are large differences among genotypes in the protein concentration at maximum grain yield (Tables 1 and 2). The protein concentration at maximum grain yield was lower for the high yielding soft white winter wheat cultivar CDC Ptarmigan than the cultivars that represented the Soft White Spring, HRWW, and CPS classes (Fig. 3B). In turn, the protein concentration at maximum grain yield was lower for the cultivars that represented the HRWW and CPS class than the HRSW cultivars, which had a very low maximum grain yield potential. The often reported strong negative correlation between cultivar grain yield and protein concentration was very evident in these comparisons (Fig. 3, r = - 0.81), translating into more than a 1/3 tonne reduction in cultivar maximum potential grain yield for every 1 % increase in GPC at maximum grain yield. This negative relationship also means that N may have to be applied at rates above those required to achieve maximum grain yield to meet minimum protein concentration targets when hard wheat cultivars with high grain yield potential are grown in high moisture environments.

The grain yield response curves flatten out at maximum grain yield (Fig. 2) with the result that large differences in GPC often translate into small differences in grain yield thereby reducing the usefulness of this part of the grain yield - GPC response curve for post-harvest assessment of N sufficiency. The response curve is much more sensitive to changes in GPC at 80 and 90 % of maximum grain yield suggesting that GPC in this region of the response curve could be used as a practical indicator of N deficiency. Coincidentally, the GPC at maximum grain yields (Tables 1 and 2) of HRS cultivars were higher than what has been suggested as post-harvest indicator of N sufficiency by other researchers (Flaten and Racz, 1997; Long and Engel, 1998; Selles and Zentner, 2001). The GPC identified in the earlier reports were more in line with the GPC at 90 % of maximum grain yield in the present study.

The results of this study demonstrate that there are large differences among wheat cultivars in grain yield-GPC relationships (Tables 1 and 2). Variation amongst cultivars tended to be less within market classes (Fig. 3B), but even in these instances the critical GPC - grain yield responses must be know for each cultivar before GPC can be used as a practical post-harvest indicator of N sufficiency. Growing season weather conditions also have a large influence on GPC-grain yield relationships (Fig. 3A), which makes the GPC - grain yield relationships environment specific. These observations indicate that GPC may be a useful post - harvest indicator of N deficiencies for crops grown under high N stress but caution must be used when the goal is to optimize N management systems.

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