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Influence of Droplet Size of Foliar-Applied Nitrogen on Grain Protein Content of Hard Red Winter Wheat

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Abstract

Effectively increasing the grain protein concentration (GPC) of hard red winter (HRW) wheat (*Triticum aestivum* L.) would allow producers to obtain adequate GPC levels while avoiding costly discounts and potentially obtaining protein premiums. The objective of this trial was to evaluate the effects of different droplet sizes and N rates applied postanthesis to winter wheat grain yield, GPC, and flag-leaf N concentrations. Foliar applications of N were made postanthesis at rates of 10 and 20 lb N/acre. Each N rate was applied at three different droplet sizes: fine, medium, coarse. The application of foliar N postanthesis did not greatly influence grain yield, but it typically increased the final GPC. The improvement in GPC was significantly related to the amount of N measured in the flag leaf after the foliar N application. Larger increases in GPC were observed when grain yields were at or above the average for the region. No consistent effect of droplet size on GPC and flag-leaf N was observed. In conclusion, applying foliar N fertilizer postanthesis potentially allows producers to effectively manage and manipulate their final GPC of HRW wheat.

Background

Wheat (*Triticum aestivum* L.) in the United States contributes significantly to cereal production in the world. Although wheat production in the United States has declined since peaking in the early 1980s, the United States still ranks as one of the top producing countries in the world, with more than 46 million acres harvested (USDA-NASS, 2016). Hard red winter wheat, which is grown extensively in the Great Plains, accounts for 40% of the total wheat grown in the United States and is primarily used for bread flour (USDA-ERS, 2012). The GPC level of HRW wheat determines the degree of milling and baking quality of processed wheat products, and the price. The HRW wheat class is considered high-protein wheat when analyzed against other classes, excluding hard red spring wheat (Bale and Ryan, 1977). Woolfolk et al. (2002) described the GPC market requirements that have been established worldwide, with higher-protein wheat receiving a higher price than lower-protein wheat, a price differential most commonly known as a protein premium. As of 30 Nov. 2010, deliverable grades of HRW wheat must contain a GPC of at least 11.0% or a $0.10/bu discount to the contract price will be applied for a GPC between 10.5 and

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Core Ideas

- Application of foliar-applied N postanthesis increased grain protein concentration (GPC).
- Increasing GPC of wheat may allow producers to avoid costly discounts and obtain premiums.
- No differences were observed in performance among three common agronomic droplet sizes.
- Improvement in GPC is related to the amount of N measured in the flag leaf after foliar N application.
- Larger increases in GPC are observed when grain yields are at or above average.

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Abbreviations: ATV: all-terrain vehicle; GPC, grain protein concentration; HRW, hard red winter; LCB, Lake Carl Blackwell; NUE, N use efficiency; OSU, Oklahoma State Univ.; PRK, Perkins; STW, Stillwater.

Conversions: For unit conversions relevant to this article, see Table A.

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Table A. Useful conversions.

To convert Column 1 to Column 2, multiply by	Column 1 Suggested Unit	Column 2 SI Unit
0.304	foot, ft	meter, m
2.54	inch	centimeter, cm (10^{-2} m)
25.4	inch	millimeter, mm (10^{-2} m)
0.405	acre	hectare, ha
35.24	bushel (dry), bu	liter, L (10^{-3} m^3)
67.19	60-lb bushel per acre, bu/acre	kilogram per hectare, kg/ha
1.12	pound per acre, lb/acre	kilogram per hectare, kg/ha
6.90	pound per square inch, lb/sq inch	kilopascal, kPa
10-percent	% gram per kilogram	g/kg

11.0% (Reuters, 2010). The new guideline set by the Kansas City Board of Trade has imposed a stricter policy for managing and producing HRW wheat. Along with increasing prices of inputs (land prices, machinery, fertilizer, and seed), producers continually need to adopt more efficient management practices to ensure that GPC is at adequate levels to maintain or increase profit margins on their wheat operations.

The GPC of winter wheat can be highly variable from one location and year to the next, with average values ranging between 8.0 and 20.0% (Kramer, 1979). Much of this variability in GPC can be attributed to environmental and genetic factors (Kramer, 1979). Rao et al. (1993) reported that GPC is not controlled by one specific factor but, rather, by many, including environment, cultivar selection, N fertilizer rate, and N application timing. Soil N availability and soil water stress are major factors affecting GPC, and in most cases GPC increases with higher temperatures and reduced rainfall (Rao et al., 1993; Debaeke et al., 1996; Gooding and Davies, 1997; Daniel and Triboi, 2000; Stone and Savin, 2000; Garrido-Lestache et al., 2004). Variability in N levels during the crop growing season can have tremendous influences on vegetative biomass, grain yield, and GPC of winter wheat. Grain protein content will not increase until N requirements for the potential yield of the crop are achieved (Bly and Woodward, 2003). When N levels are low, additional applications of N fertilizer will increase crop yield until the yield curve levels off, indicating that less grain is being produced per unit of N applied (Kramer, 1979). When the yield curve reaches its plateau, N is no longer the most limiting factor for grain yield and GPC will increase with additional N applications (Gauer et al., 1992). Research conducted on late-season N applications as either dry or liquid material has shown an increase in GPC (Fowler and Brydon, 1989; Woolfolk et al., 2002; Bly and Woodward, 2003). Applications of late foliar N fertilizer have proven to improve N use efficiency (NUE) and promote an increase in GPC compared with excess N being applied preplant (Raun and Johnson, 1993; Wuest and Cassman, 1992a, 1992b). According to Bly and Woodward (2003), with a post-pollination foliar N application, GPC was increased 70% of the time when potential grain yield was exceeded and 23% when potential grain yield was not exceeded . Woolfolk et al. (2002) reported that wheat grain N, which is indicative of GPC, was increased by 0.3 and 0.2% with late-season foliar N applications before and immediately following flowering, respectively.

It has been reported that during grain development the protein yield or grain N is source dependent (Martre et al., 2003; Gooding et al., 2007). The N required in the developing grain for protein synthesis is derived from two pathways: N previously assimilated, prior to anthesis, and present in vegetative tissue; and N taken up directly from the soil (Guohua et al., 2000). The N accumulated preanthesis and then remobilized to the grain is known to be the main source of N during grain development and accounts for half to almost all of the grain N (Spiertz and Ellen, 1978; Van Sanford and MacKown, 1987; Heitholt et al., 1990). The remaining grain N is thought to come from the postanthesis N uptake, with the amount being dependent on plant N status, plant available water, and genotypic differences. (Cox et al., 1985, Wuest and Cassman, 1992a, 1992b; Barbottin et al., 2005).

When applying liquid products, such as foliar N fertilizer, through commercial sprayers, the main objective is to apply an effective layer onto the crop's leaf surface. Lake (1977) described an effective product application on the leaf surface to be one that achieves acceptable control while still maintaining a practical application rate. Factors that affect whether the application was retained on the leaf's surface depend on several factors: droplet size, velocity of the droplet, trajectory from the sprayer, and the physical properties of the spray liquid and leaf surface (Lake, 1977; Miller and Butler Ellis, 2000). It has been reported that decreasing the size of the droplet leads to an increase in uptake of active ingredient and increased spread area by providing improved leaf coverage and droplet deposition (Mercer, 2007; Wolf et al., 2009). The opposite trend is typically observed when the size of the droplet increases; however, larger droplets are able to retain momentum longer and are less susceptible to drift (Tuck et al., 1997).

The ability to effectively increase the GPC of HRW wheat late in the growing season could allow producers to obtain adequate GPC levels and thus not suffer potential revenue losses. Previous work has shown the potential for late-season improvements to GPC with the addition of foliar N fertilizer; however, best agronomic management practices need to be evaluated to ensure that the most efficient and effective procedures are utilized. The objective of this study was to evaluate the effects of droplet size and N rate of postanthesis foliar N-fertilizer applications on GPC of HRW wheat.

Experimental Sits and Application of Treatments

Three sites in north-central Oklahoma were selected to conduct this study: Stillwater (STW), a Norge loam (fine-silty, mixed, active, thermic Udic Paleustolls); Lake Carl Blackwell (LCB), a Port silt loam (fine-silty, mixed, superactive, thermic Cumulic Haplustolls); and Perkins (PRK), a Konawa (fine-loamy, mixed, active, thermic Ultic Haplustalfs) (Soil Survey Staff, 2016). At each site, studies were conducted during both the 2011–2012 and 2012–2013 growing seasons. From this point forward, each growing season will be referred to by the year of grain harvest.

For each site-year, seven fertilizer treatments were arranged in a randomized complete block design with three replications (Table 1). In 2012, LCB and PRK plot sizes were 10 by 30 ft, and STW had a plot size of 10 by 20 ft. In 2013, LCB and STW plots were 10 by 20 ft, while PRK had plots of 10 by 30 ft. Preplant N and P fertilizer was broadcast applied, and additional N was applied topdress (Feekes 4 or 5) to all treatments when needed to maximize grain yield potential. Table 2 describes surface (0–6 inches) residual soil NO_3–N levels, fertilization, planting, foliar N application, and harvesting times for all sites. Figure 1 reports the monthly rainfall and average air temperature during the growing season for each site-year.

For all site-years, foliar N was applied in the form of urea–ammonium nitrate (28% N) mixed in a 1:1 by volume solution with water in an attempt prevent excessive foliar burn. Foliar N applications were applied postanthesis (Feekes 10.5.3) at each site (Large, 1954). Three droplet sizes with different volume median diameters—fine (106 to 235 microns), medium (236 to 340 microns), and coarse (341 to 403 microns)—were established for this experiment using manufacturer's nozzle tip specifications and the ASABE Standard S572.1 (ASABE, 2009). In addition, two foliar N rates—10 and 20 lb N/acre—were used with each droplet size. The treatment structure and nozzle tip type that was employed for each site-year are listed in Table 1. All nozzle tips were manufactured and donated by HYPRO Global Spray Solutions (New Brighton, MN). The foliar urea–ammonium nitrate treatments were applied 20 inches above the crop canopy using an all-terrain vehicle (ATV) equipped with a 10-ft spray boom and nozzles 20 inches apart. Foliar N rate and droplet size for each specific treatment were controlled using a pressurized canister with a pressure valve, nozzle tip type, and a previously determined groundspeed.

Table 1. Treatment structure describing N rate and droplet size for all site-years.

Treatment	Foliar N rate	Droplet size†	Nozzle‡	Pressure	Speed
	lb N/ac			lb/sq inch	mi/h
1	0	—	—	—	—
2	10	fine	FC-TR110–015	25	5
3	10	medium	GRD120–01	60	5
4	10	coarse	GRD120–015	25	5
5	20	fine	FC-TR110–02	60	5
6	20	medium	GRD120–02	60	5
7	20	coarse	GRD120–02	40	6

†Droplet size according to ASABE (2009).

‡Nozzle type according to HYPRO Global Spray Solutions (New Brighton, MN).

Determination of Grain Yield, Flag-Leaf N, and Grain Protein Concentration

Three to 5 days following application of foliar N treatments; fifteen flag leaves were randomly collected in each plot for total N analysis. At crop maturity, the center 5 ft of each plot was harvested using a Massey Ferguson 8XP (Massey Ferguson, Duluth, GA) small-plot combine equipped with subsampling and yield data-collection capabilities. During trial harvest, grain subsamples were collected and analyzed for grain moisture content for each plot. Plot grain yield was adjusted to a standard moisture of 12.5%. Both flag-leaf and grain subsamples were oven dried and processed to pass a 140-mesh screen with a Wiley Mill (Thomas Scientific, Swedesboro, NJ) tissue grinder and further analyzed for total N with a LECO Truspec (LECO Corporation, St. Joseph, MI) CN dry combustion analyzer (Schepers et al., 1989). Grain protein concentrations were calculated with the following total grain N to GPC conversion factor: total grain N (%) × 5.7 (Tkachuk, 1977; Martin del Molino, 1991).

Data Analysis

Grain yield, GPC, and flag-leaf total N data were analyzed with JMP Pro Version 10.0 (SAS Institute Inc., Cary, NC). The effects of droplet size and N rate on each dependent variable for each site-year, as well as across site-years, were evaluated with analysis of variance techniques and single degree-of-freedom, non-orthogonal contrasts. Linear regression analysis was employed to evaluate the relationship between grain yield, GPC, and flag-leaf total N concentration.

Site-year Growing Conditions and Observations

Growing conditions for 2012 were thought to be below adequate for high-quality winter wheat production. Below-average rainfall in the month of May (Fig. 1) overlapped the critical grain-filling period and probably led to below-average grain yields for all sites. A late-season outbreak of leaf rust also infected all trials and reduced the flag-leaf surface area, especially for the PRK site. Foliar N applications at PRK and LCB were made prior to unexpected rainstorms that

Table 2. Production system, planting, and fertilization information for Lake Carl Blackwell, OK (LCB), Stillwater, OK (STW), and Perkins, OK (PRK) research sites studying the effects of foliar N applications on winter wheat during the 2011–12 and 2012–13 growing seasons.

	LCB		STW		PRK	
	2012	2013	2012	2013	2012	2013
Tillage system	no-till	conventional	no-till	no-till	no-till	no-till
Variety	Endurance	Duster	Centerfield	Duster	Centerfield	Duster
Planting date	14 October	12 November	15 October	12 October	13 October	8 October
Seeding rate (lb/acre)	90	90	90	90	90	90
Residual NO_3 (lb N/acre)	32	26	20	24	14	7
Preplant N, P_2O_5 (lb/acre)	40, 0	60, 25	0, 0	40, 0	0, 0	40, 0
Topdress N (lb/acre)	40	0	0	40	40	40
Foliar N date	13 April	13 May	25 April	14 May	13 April	13 May
Application (temp., °F; humidity, %; wind, mi/h) †	68, 79, 9	70, 48, 7	75, 52, 9	75, 38, 11	68, 79, 11	72, 36, 11
Grain harvest date	4 June	25 June	11 June	20 June	12 June	14 June

†Average weather conditions 4 h after foliar N application (Mesonet, 2016).

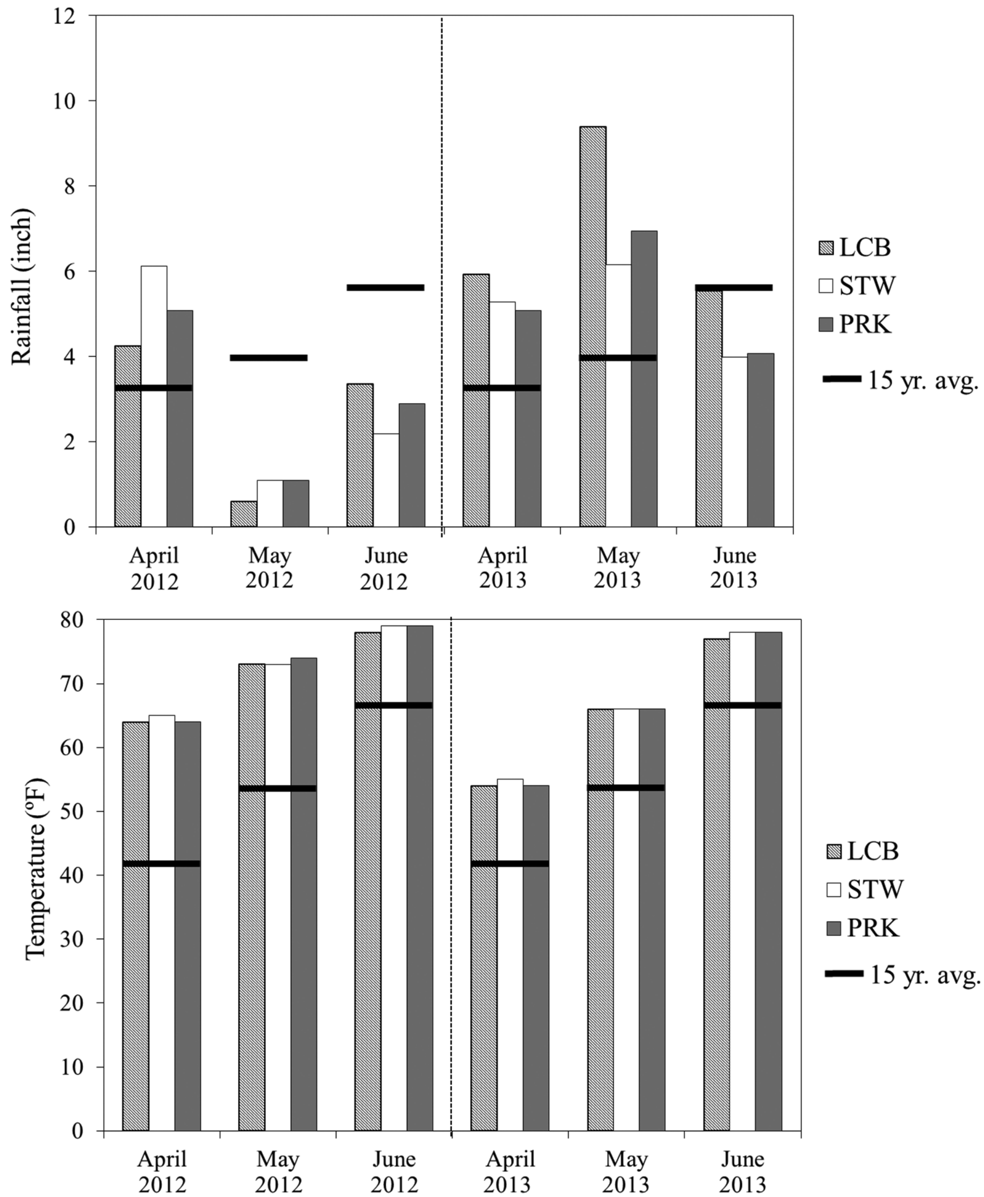

Fig. 1. Monthly rainfall totals and average temperatures for Lake Carl Blackwell, OK (LCB), Stillwater, OK (STW), and Perkins, OK (PRK) (Mesonet, 2016).

brought 0.2 and 0.6 inches of rain within 8 h of foliar N application, respectively. At STW, foliar applications were made after the rainfall event. At all sites in 2012, foliar burn was extremely minimal or nonexistent, and if it was observed, it was located on the awns of the wheat heads. Growing conditions during the 2013 season started off very poorly with drought conditions well into the later part of winter. Around spring green-up, precipitation amounts increased, leading to an increase in plant tillering and more-uniform plant stands. Unlike 2012, the 2013 growing season received above-average rainfall at all three sites during the month of May (Fig. 1). In 2013 at all locations, all fertilized treatments showed minimal signs of awn burn from foliar N applications but not any damage to the flag leaves. Based on the observations from 2012 and 2013, no significant grain yield decreases due to foliar burn were observed during the study.

Grain Yield Response

When the treatment effects on grain yield across sites and years were evaluated, the analysis of variance revealed a significant ($\alpha = 0.10$) interaction effect of site, year, and treatment (Table 3). Because of these results, only the analysis of variance and contrast results by site-year are reported. Treatment means and single degree-of-freedom contrast results for grain yield, GPC, and flag-leaf N are reported by site in Tables 4–6 for LCB, STW, and PRK, respectively. Typical wheat grain yield for the region averages 33 bu/acre and can range from 15 to 75 bu/acre (USDA-NASS, 2016). Grain yields varied greatly across sites and years during this study. Average grain yields in 2012 were 24.3, 29.2, and 16.9 bu/acre at LCB, STW, and PRK, respectively. Decreased grain yields were expected at PRK, compared with the other two sites, due to an observed higher incidence of damage from leaf rust along with the sandier composition of the soil, which reduced the amount of plant-available water during the drier month of May. Average grain yields in 2013 were 62.7, 25.5, and 27.4 bu/acre at LCB, STW, and PRK, respectively. There was no statistically significant improvement in grain yield with the addition of foliar N for any of the site-years (Tables 4–6). This was expected following similar work conducted by Dick et al. (2016) and Woolfolk et al. (2002), in which no increases in significant grain yield were observed with postanthesis foliar

Table 3. Analysis of variance for the effects of year, location, and the addition of foliar-applied N at different droplet sizes on hard red winter wheat grain yield, grain protein content (GPC), and flag-leaf N concentrations.

Source of variation	df†	Grain yield	GPC	Flag-leaf N
			$P > \|t\|$	
Year (Y)	1	<0.001	<0.001	<0.001
Location (L)	2	<0.001	<0.001	<0.001
Y × L	2	<0.001	0.001	<0.001
Treatment (T)	6	0.705	0.015	0.001
Y × T	6	0.055	0.593	0.653
L × T	12	0.362	0.627	0.209
Y × L × T	12	0.057	0.737	0.508

†df, degrees of freedom.

N applications. No consistent difference was observed in the effect of N rate on grain yield. The only statistical difference between the 10 and 20 lb N/acre treatments that was observed was at PRK in 2013, in which the 20-lb N rate yielded 2.9 bu/acre more than the 10-lb rate (Table 6). With regard to droplet size, there were no consistent or specific droplet sizes that provided a superior improvement in grain yield (Tables 4–6). The medium-size-droplet treatments did have numerically higher grain yields at four of the six site-years (Tables 4–6); however, the only statistically significant difference occurred at LCB in 2013, when the medium-size droplets were compared with the coarse-size droplets (Table 4).

Grain Protein Concentration Response

Grain protein concentrations for winter wheat in the region typically range between 8.0 and 20.0% (Kramer, 1979). Grain protein concentrations were variable across all site-years. The lowest GPC levels occurred at LCB in 2012 and can probably be attributed to loss in foliar N because of the rainfall that occurred shortly after (<8 h) foliar N application (Table 4). Also the variety (Endurance) that was used at LCB in 2012 is typically classified as a lower-protein variety, especially compared with the other two varieties (Duster, Centerfield) used in this trial (OSU Wheat Improvement Team, 2006a, 2006b; Edwards et al., 2015). For the other site-years, the average GPC values were consistently above the 11.0% threshold for the application of discounts established by the Kansas City Board of Trade (Reuters, 2010). The addition of foliar N fertilizer numerically increased GPC values at four of the six site-years (Tables 4–6). The increase ranged between 0.5 and 1.1%, with the largest, and only statistically significant, increase occurring at LCB in 2013 (Table 4). It was also observed that the two highest increases in GPC were from STW 2012 and LCB 2013, the only two sites not to receive any topdress N during the growing season. No statistical differences in GPC were observed between the two N rates at any of the site-years (Tables 4–6); however, at five of the six site-years, the GPC levels were numerically higher for the 20 lb N/acre application rate (Tables 4–6). Statistically, there were no differences for the effect of droplet size on GPC (Tables 4–6). However, for five of the six site-years, the medium- and/or coarse-sized droplets displayed numerically higher GPC values when compared with the fine-droplet treatments.

The interactive effect of treatments and site-years on GPC was observed to be not statistically significant (Table 3). As a result, the effects of treatments could be analyzed with data pooled across sites and years. These results did reflect that there was a statistically significant effect of treatment (Table 7). Non-orthogonal contrasts revealed that regardless of N rate, the application of foliar N fertilizer significantly increased GPC when compared with the untreated check (Table 7). An increase in GPC was observed for the 20 lb N/acre treatment compared with the 10 lb N/acre treatment and was significant at the 0.10 α level (Table 7). The results of the pooled-analysis effect of droplet size on GPC revealed no specific droplet size performed better than the other (Table 7).

Table 4. Treatment means, analysis of variance, and single degree-of-freedom contrast results for the effects of foliar N rate and droplet size on winter wheat grain yield, grain protein concentration (GPC), and flag-leaf N concentration at Lake Carl Blackwell, OK.

Treatment	Foliar N rate	Droplet size	2012 Grain yield	2012 GPC	2012 Flag-leaf N	2013 Grain yield	2013 GPC	2013 Flag-leaf N
	lb N/acre		bu/acre	%	%	bu/acre	%	%
1	0	—	27.6	9.2	2.8	59.8	12.7	3.5
2	10	fine	20.4	8.8	2.8	67.8	14.0	3.8
3	10	medium	24.9	9.0	2.8	58.8	13.4	3.8
4	10	coarse	20.6	9.2	3.0	65.6	13.6	3.8
5	20	fine	24.9	8.8	2.7	59.8	14.3	3.8
6	20	medium	32.3	9.4	2.8	64.2	14.1	3.9
7	20	coarse	19.2	9.0	2.7	62.7	13.2	3.7
		SED†	4.2	0.3	0.1	3.2	0.6	0.2
		$P > \|t\|$	0.085	0.460	0.425	0.106	0.184	0.396
Contrasts‡								
Check vs. other			NS§ (3.8)	NS (0.1)	NS (−0.1)	NS (−3.3)	* (−1.1)	* (−0.3)
10 vs. 20 lb N/acre			NS (−3.5)	NS (−0.1)	NS (0.1)	NS (1.8)	NS (−0.2)	NS (−0.1)
Fine vs. medium			NS (−5.9)	NS (−0.4)	NS (−0.1)	NS (2.3)	NS (0.4)	NS (−0.1)
Fine vs. coarse			NS (2.7)	NS (−0.3)	NS (−0.1)	NS (−0.4)	NS (0.8)	NS (0.1)
Medium vs. coarse			* (8.6)	NS (0.1)	NS (−0.1)	NS (−2.7)	NS (0.4)	NS (0.1)
Fine, medium vs. coarse			* (5.7)	NS (−0.1)	NS (−0.1)	NS (−1.5)	NS (0.6)	NS (0.1)

*Significant at the 0.05 probability level.

†Standard error of the difference between two equally replicated means.

‡Values in parenthesis are the difference between the first grouping mean and second grouping mean.

§ NS, not significant at the 0.05 probability level.

Table 5. Treatment means, analysis of variance, and single degree-of-freedom contrast results for the effects of foliar N rate and droplet size on winter wheat grain yield, grain protein concentration (GPC), and flag-leaf N concentration at Stillwater, OK.

Treatment	Foliar N rate	Droplet size	2012 Grain yield	2012 GPC	2012 Flag-leaf N	2013 Grain yield	2013 GPC	2013 Flag-leaf N
	lb N/acre		bu/acre	%	%	bu/acre	%	%
1	0	—	33.4	13.1	2.4	24.0	15.2	3.2
2	10	fine	27.1	13.6	2.5	25.8	15.7	3.5
3	10	medium	30.8	13.5	2.3	29.3	15.5	3.2
4	10	coarse	28.9	14.0	2.8	25.8	15.9	3.3
5	20	fine	25.7	14.2	2.7	27.3	16.1	3.5
6	20	medium	30.7	14.6	2.8	22.9	16.2	3.4
7	20	coarse	27.8	13.6	3.1	23.7	16.1	3.5
		SED†	5.1	0.5	0.2	3.0	0.6	0.2
		$P > \|t\|$	0.772	0.148	0.089	0.424	0.571	0.718
Contrasts‡								
Check vs. other			NS§ (4.8)	NS (−0.8)	NS (−0.3)	NS (−1.8)	NS (−0.8)	NS (−0.2)
10 vs. 20 lb N/acre			NS (0.9)	NS (−0.4)	NS (−0.3)	NS (2.3)	NS (−0.4)	NS (−0.2)
Fine vs. medium			NS (−4.3)	NS (−0.1)	NS (0.1)	NS (0.5)	NS (0.1)	NS (0.2)
Fine vs. coarse			NS (−1.9)	NS (0.1)	NS (−0.3)	NS (1.8)	NS (−0.1)	NS (0.1)
Medium vs. coarse			NS (2.4)	NS (0.3)	* (−0.4)	NS (1.3)	NS (−0.1)	NS (−0.1)
Fine, medium vs. coarse			NS (0.2)	NS (0.2)	* (−0.4)	NS (1.5)	NS (−0.1)	NS (0.1)

*Significant at the 0.05 probability level.

†Standard error of the difference between two equally replicated means.

‡Values in parenthesis are the difference between the first grouping mean and second grouping mean.

§NS, not significant at the 0.05 probability level.

Table 6. Treatment means, analysis of variance, and single degree-of-freedom contrast results for the effects of foliar N rate and droplet size on winter wheat grain yield, grain protein concentration (GPC), and flag-leaf N concentration at Perkins, OK.

Treatment	Foliar N rate	Droplet size	2012			2013		
			Grain yield	GPC	Flag-leaf N	Grain yield	GPC	Flag-leaf N
	lb N/acre		bu/acre	%	%	bu/acre	%	%
1	0	—	18.5	12.1	2.4	25.4	12.9	2.0
2	10	fine	17.5	11.9	2.6	27.9	13.2	2.4
3	10	medium	18.6	11.7	2.7	26.3	13.0	2.4
4	10	coarse	16.1	11.9	2.5	24.7	13.7	2.6
5	20	fine	17.3	11.8	2.7	28.3	13.2	2.5
6	20	medium	13.0	12.1	2.6	30.5	13.2	2.5
7	20	coarse	17.1	12.3	2.9	28.9	13.6	2.5
		SED†	2.4	0.4	0.1	2.1	0.7	0.2
		$P > \|t\|$	0.337	0.606	0.090	0.165	0.865	0.135
Contrasts‡								
Check vs. other			NS§ (1.9)	NS (0.1)	* (−0.3)	NS (−2.4)	NS (−0.5)	* (−0.5)
10 vs. 20 lb N/acre			NS (1.6)	NS (0.2)	NS (−0.2)	* (−2.9)	NS (−0.1)	NS (−0.1)
Fine vs. medium			NS (1.6)	NS (−0.1)	NS (−0.1)	NS (−0.3)	NS (0.1)	NS (0.1)
Fine vs. coarse			NS (0.8)	NS (−0.3)	NS (−0.1)	NS (1.4)	NS (−0.5)	NS (−0.1)
Medium vs. coarse			NS (−0.8)	NS (−0.2)	NS (0.0)	NS (1.6)	NS (−0.6)	NS (−0.1)
Fine, medium vs. coarse			NS (0.0)	NS (−0.2)	NS (0.0)	NS (1.5)	NS (−0.5)	NS (−0.1)

*Significant at the 0.05 probability level.

†Standard error of the difference between two equally replicated means.

‡Values in parenthesis are the difference between the first grouping mean and second grouping mean.

§NS, not significant at the 0.05 probability level.

Table 7. Treatment means, analysis of variance, and single degree-of-freedom contrast results for the effects of foliar N rate and droplet size on winter wheat grain protein concentration (GPC) and flag-leaf N concentration across all six site-years.

Treatment	Foliar N rate	Droplet size	GPC	Flag-leaf N
	lb N/acre		%	%
1	0	—	12.5	2.7
2	10	fine	12.9	2.9
3	10	medium	12.7	2.9
4	10	coarse	13.1	3.0
5	20	fine	13.1	3.0
6	20	medium	13.3	3.0
7	20	coarse	12.9	3.1
		SED†	0.2	0.1
		$P > \|t\|$	0.015	0.001
Contrasts‡				
Check vs. other			* (−0.5)	* (−0.3)
10 vs. 20 lb N/acre			§ (−0.2)	* (−0.1)
Fine vs. medium			NS¶ (0.0)	NS (0.1)
Fine vs. coarse			NS (0.0)	NS (−0.1)
Medium vs. coarse			NS (0.0)	§ (−0.1)
Fine, medium vs. coarse			NS (0.0)	§ (−0.1)

*Significant at the 0.05 probability level.

†Standard error of the difference between two equally replicated means.

‡Values in parenthesis are the difference between the first grouping mean and second grouping mean.

§Significant at the 0.10 probability level.

¶NS, not significant at the 0.05 probability level.

The ability to successfully increase GPC levels as a result of postanthesis foliar-applied N has been reported in the literature (Woolfolk et al., 2002; Bly and Woodward, 2003; Dick et al., 2016). Using similar N rates to those used in this study, Woolfolk et al. (2002) observed GPC (estimated from grain N data) could be increased on average by about 1.1% and as much as 2.1%. Bly and Woodward (2003) showed that the potential for an increase in GPC with the addition of post-flowering foliar-applied N was more likely to occur when the yield potential for the wheat has been met. This trend appears to hold true for the data in this study. As previously stated, the average grain yield for the region is approximately 33 bu/acre (USDA-NASS, 2016). The only site-year that had an average grain yield that exceeded this amount was the LCB 2013 site, which was the site-year that displayed the greatest increase in GPC with the addition of foliar N fertilizer (Table 4).

Flag-Leaf N Response

At the time of the foliar N application in this trial, the plant part with the greatest area that could intercept the foliar N spray would be the flag leaf. Along with other green vegetative structures, the flag leaf should act as a storage site for the previously accumulated N, which accounts for the majority of the N remobilized to the grain for protein development (Spiertz and Ellen, 1978; Van Sanford and MacKown, 1987; Heitholt et al., 1990). It was hypothesized that the direct application of N fertilizer to the leaves, as in this study, had the potential to increase GPC. A wide range of flag-leaf N

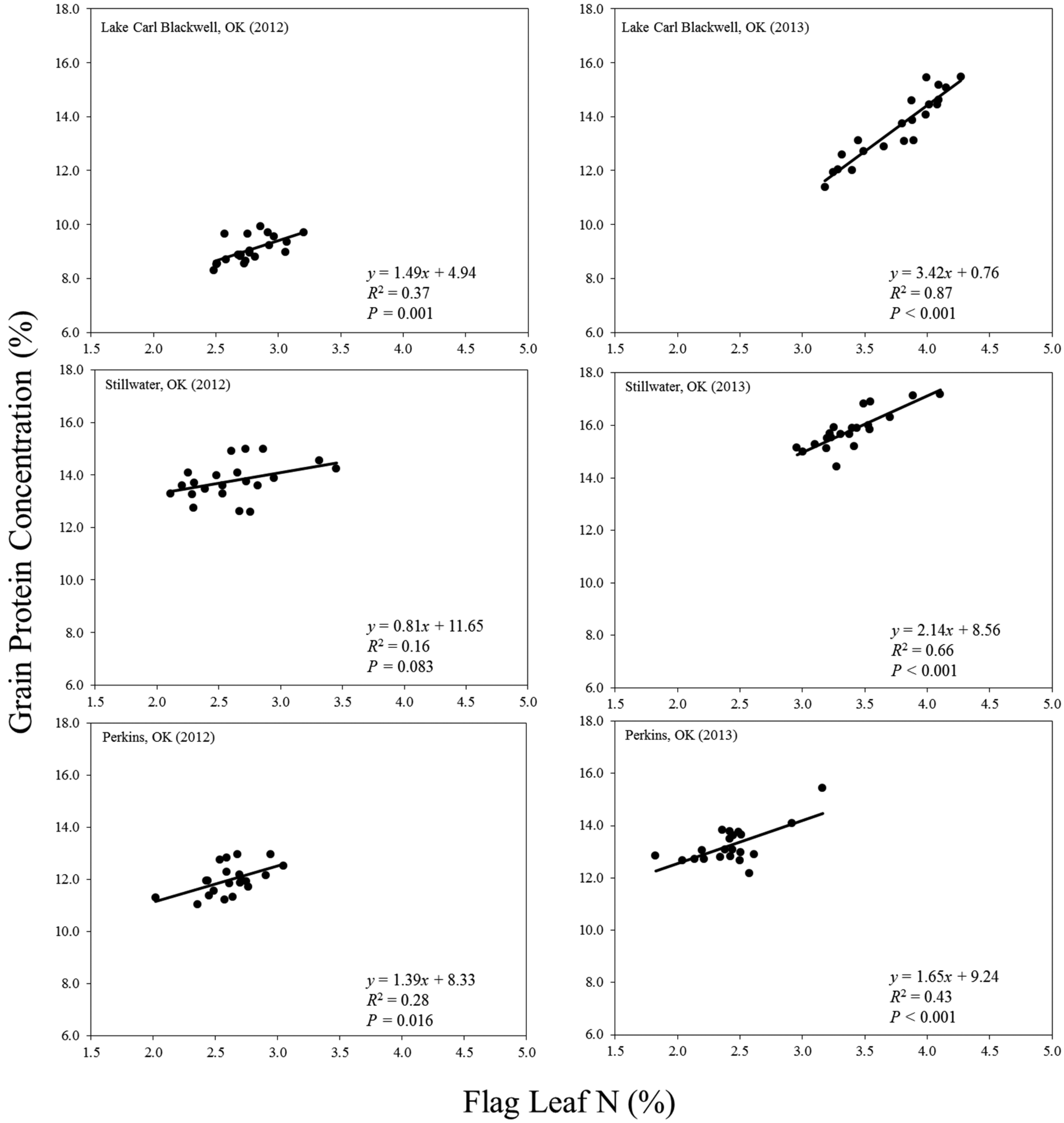

Fig. 2. Linear regression analysis depicting the relationship between flag-leaf N concentration and grain protein concentration.

concentrations was observed, with a range in values from 2.0 to 3.9% N across all site-years (Tables 4–6). When compared with flag leafs that received no foliar N fertilizer, treatments that received foliar N fertilizer had flag leaves with higher N concentrations at all site-years, and this relationship was statistically significant for LCB in 2013 and PRK in 2012 and 2013 (Tables 4–6). The 20 lb N/acre rate treatments also displayed numerically higher flag-leaf N concentrations compared with the 10 lb N/acre treatments, but these were not statistically significant for any of the six site-years. Much like for grain yield and GPC, there was no consistent effect or specific droplet size that provided the highest flag-leaf N concentrations. The coarse droplets did have numerically higher flag-leaf N concentrations for three of the six site-years, but this relationship was statistically significant only for the STW 2012 site.

As was observed for GPC, the interactive effect of treatments and site-years on flag-leaf N was observed to be not statistically significant (Table 3). As a result, the effect of treatments could be analyzed with data pooled across site-years. The addition of foliar N fertilizer significantly increased flag-leaf N concentrations when plots receiving foliar fertilizer were compared with the untreated check (Table 7). There was also a significant effect on flag-leaf N of increased rates of foliar applied N fertilizer (Table 7). There were no significant differences observed between the three droplet sizes at the 0.05 α level; however, the coarse-sized droplets did have significantly higher flag-leaf N concentrations at the 0.10 α level when compared with the fine and medium-sized droplets (Table 7).

Relationship between Flag-Leaf N and Grain Protein Content

To determine the potential effects the flag-leaf N concentrations could have on grain yield and GPC, linear regression analysis was used to compare the different variables. There was no statistically significant correlation observed for flag-leaf N and grain yield for any of the six site-years evaluated (data not reported). This finding is consistent with work by Jenner et al. (1991), who observed that delayed senescence of the flag leaf by late-season N fertilizer application will not increase grain development and thus grain yield. Significant linear relationships were observed between flag-leaf N and GPC at five of the six site-years (Fig. 2). These relationships showed that as flag-leaf N concentrations increased, so did the GPC; however, the relationships were not necessarily similar between site-years based on slopes and intercepts (Fig. 2). Numerous factors from genetics to environmental conditions could have influenced the relationship of how much of the flag-leaf N was potentially remobilized from the flag leaf to the grain for protein production.

Conclusions and Recommendations

For ground-based agrichemical applications, the varying sizes of droplets used in this study are typical for what might be employed by agricultural producers in the region. Although there were limited, statistically different results for the effect of droplet size on grain yield, GPC, and flag-leaf N concentrations, one observable trend at some of the site-years was that the medium- and/or coarse-sized droplets tended to perform better at increasing the GPC and flag-leaf N concentrations. This observation probably occurred because small droplets are more prone to drift and can have poor leaf retention (Knoche, 1994). Decreased droplet size may also not be as favorable for N applications, because they have an increased potential for ammonia volatilization losses and are more prone to leaf burn (Edwards et al., 2013). Because these recommendations are based on results that are not statically significant, they should be accepted with caution until the conclusions are nullified or validated with more data.

Effectively increasing the GPC of HRW wheat postanthesis could allow producers to obtain adequate GPC levels and avoid potential discounts on grain delivery and obtain potential premiums. Results from this trial supported previous work and demonstrated the potential for late-season increases in GPC with the addition of foliar N fertilizer. As was observed by other researchers, the application of foliar N postanthesis did not greatly influence grain yield but, instead, typically increased the final GPC. The improvement in GPC was significantly related to the amount of N measured in the flag leaf after foliar N was applied. Larger increases in GPC were observed when grain yields were at or above the average for the region. In conclusion, producers have the ability to effectively manage and manipulate their final GPC of HRW wheat. They can do so with knowledge of the genetics of their varieties, having an estimate of their yield potential, and employing proper agronomic practices, such as utilizing proper spray tips and applying fertilizer in an appropriate manner.

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