Managing Nitrogen and Sulfur Fertilization for Improved Bread Wheat Quality in Humid Environments

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Cereal Chem. 84(5):450–462

ABSTRACT

A large proportion of the wheat (*Triticum aestivum* L.) milled and utilized by bakeries in the eastern United States is hard red winter wheat (HRWW). Potential for producing this higher value commodity in the eastern United States is dependent on availability of adapted HRWW cultivars that are competitive with soft red winter wheat (SRWW) cultivars and implementation of management systems to enhance end-use quality. The effects of late-season nitrogen (N) (0–45 kg of N/ha) applied at two growth stages (GS 45 and 54) and sulfur (S) (0–34 kg of S/ha) applied at GS 30 on grain, flour, and milling and breadbaking quality were evaluated. Three diverse wheat cultivars (Soissons, Heyne, and Renwood 3260) were studied in two to five environments. Application of S and late-season N had little effect on grain yield. But N consistently increased grain and flour protein as well as bread loaf volume. The magnitude and significance of response to N and S varied by location and cultivar. While S alone did not have a significant effect on grain protein, S availability was critical in obtaining increased grain protein. Breadbaking quality of HRWW cultivars produced in the eastern United States can be improved through implementation of nutrient management approaches that include late-season application of 34–45 kg of N/ha and addition of S, particularly on sandy soils where S availability in the subsoil is low.

The wheat milling capacity in the Mid-Atlantic region of the United States is 2,900,000 Mg of grain/year (World Grain International 2006). A large portion of this grain is purchased by regional mills from other wheat growing areas, especially the Great Plains of North America. Some millers use only hard wheat, which is almost exclusively grown outside the Mid-Atlantic region (C. J. Lin, *personal communication*). Hard wheat and certain strong gluten soft wheat cultivars are suitable for use in making bread products. Because general market values for these types of bread are higher for hard wheat than soft wheat ($14.68/Mg or more), producers are interested in using adapted cultivars and developing agronomic techniques to grow bread wheat in the humid, high-rainfall environment of the Mid-Atlantic region. Millers in the Mid-Atlantic region are interested in obtaining locally grown bread wheat because transportation costs, and thus total cost, would be greatly reduced for grain produced in the region. Efforts in the Mid-Atlantic region to identify and breed adapted bread wheat lines have shown promise in comparison to traditional HRWW cultivars, which do not yield as well as adapted SRWW cultivars. Data from the Virginia Elite and Uniform Bread Wheat Trials indicate that current soft wheat cultivars out-yield HRWW cultivars by 0.8 to 1.3 Mg/ha.

Because N availability is frequently the main determinant of grain yield and protein concentration in wheat, sufficient N should be applied so as not to limit either grain yield or quality (Olson et al 1976; Grant et al 1985). In fact, grain protein concentration has been shown to increase at N rates above those necessary to support maximum yields (Kelley 1993). However, excessive plant-available N produces wheat plants more prone to lodging and disease development with subsequent reductions in yield and increased input costs (Crook and Ennos 1995). The potential for elevated nitrate levels in ground and surface waters also increases with excessive N fertilizer applications (Coale et al 2001). Late-season N applications to wheat have increased nitrogen use efficiency and produced similar yields with less total N by matching N application timing with plant demand (Ellen and Spiertz 1980). However recent work has reported lower apparent fertilizer recovery from the late-season nitrogen application when N supplied earlier in the season was adequate to achieve optimum yields (Gooding et al 2007).

Wheat yield and protein concentration are inversely related due to energy constraints and dilution effects within the plant (Pearman et al 1978; Halloran 1981). Under favorable growing conditions, starch and protein increase simultaneously, but under water and temperature stress, the conversion of sucrose to starch may be hindered. Protein formation is much less affected by these conditions and protein level is typically greater in wheat grown under stress of water and temperature (Brooks et al 1982; Bhullar and Jenner 1986). Because cultivars of SRWW grown within wet, humid environments are typically lower in grain protein than HRWW produced in drier production areas (Dimmock and Gooding 2002) and because relatively high grain protein levels are needed for bread production, additional breeding and management techniques are both required to increase grain protein concentration with minimal economic and environmental impacts.

Increased grain protein concentration resulting from late-season foliar N application has been demonstrated in bread wheat in other regions (Wuest and Cassman 1992; Phillips et al 1999; Woolfolk et al 2002) and has only recently been examined in more humid areas, and then grain protein was the only quality parameter reported (Kratochvil et al 2005).

Baking quality of wheat flour typically increases with increased grain protein (Randall et al 1990), which is a major indicator of bread wheat quality, especially as related to loaf volume (Stoddard and Marshall 1990). Extremely high-protein concentration can result in decreased breadmaking quality because N is accumulated in grain as gliadins or nonprotein N fractions (Borghi 1999). Rate and timing of N application affect breadmaking quality (Guttieri et al 2005), with late-season application typically increasing grain protein levels (Wuest and Cassman 1992). Increased grain protein concentration does not always result in increased breadmaking quality because of the imbalance in N and S content as protein level increases (Timms et al 1981; Stoddard and Marshall 1990). Limited S availability favors the synthesis of low-S gliadin storage proteins and high molecular weight subunits of glutenin at the expense of S-rich proteins (Wrigley et al 1980). Sulfur deficiency decreases the quantity of polymeric proteins and shifts the distribution from polymeric to lower molecular weight proteins (MacRitchie and Gupta 1993). These changes in protein composition are associated with alterations of dough rheology. Research in New Zealand has demonstrated that sulfur fertilizer decreases dough mixing time and work requirements compared with N alone or no

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doi:10.1094/CCHEM-84-5-0450

fertilizer (Wooding et al 2000a,b). Zhao et al (1999) found that S fertilization increased loaf volume and dough extensibility but decreased dough resistance. In general, they reported that S is more likely to affect breadmaking quality parameters than to increase grain yield or protein concentration.

Objectives of the current research were to determine the optimum rate and timing for late-season N applications to bread wheat and to evaluate the effect of late-season foliar N and S applications on bread wheat yield, grain protein, and milling and baking quality in the humid Mid-Atlantic region.

MATERIALS AND METHODS

Field experiments were conducted during the 2001 crop season at the Virginia Crop Improvement Farm, Mt. Holly, VA, on a State fine, sandy, loam soil (Fine loamy, mixed, semiactive thermic Typic Hapladult). Experiments conducted from 2002 to 2003 at the Eastern Virginia Agricultural Research and Extension Center, Warsaw, VA, were on a Kempsville loam (Fine-loamy, silicious, subactive, thermic Typic Hapludult) and those at the Eastern Shore Agricultural Research and Extension Center, Painter, VA, were on a Bojac sandy loam soil (Coarse-loamy, mixed, semiactive, thermic Typic Hapludult). The Bojac soil has a Bt (clay) layer defined at 20 cm while the Bt layer occurs at 36–38 cm in the State and Kempsville soils. A split-plot design with eight replicates (blocks) was deployed to evaluate late-season N rates and timing in subplots 1.1 m × 6.99 m. Sulfur, the main plot factor, was applied at a rate of 34 kg of S/ha to four of the eight replicates at GS 30 in each year, resulting in this effect being nested within the replication effect. At the Painter site, and in the 2001 study at Mt. Holly, treatments were applied only to the French bread wheat cultivar Soissons, released by Florimond Desprez. Soissons has unique end-use characteristics, is late heading, short in stature with excellent straw strength, and produces grain that is semi-hard in texture with moderate protein content and very high gluten strength. In the 2001-02 and 2002-03 studies at Warsaw, two additional wheat cultivars, Heyne and Renwood 3260, with diverse quality characteristics, were planted and evaluated with Soissons in adjacent areas within the same experimental blocks. Heyne is a hard white winter wheat cultivar released by Kansas State University that is moderately late heading, short in stature with very good straw strength, and produces grain that is hard in texture with high protein content and high gluten strength. Renwood 3260 is a SRWW cultivar released by Virginia Tech that is early heading, moderately short in stature with good straw strength, and produces grain that is soft in texture with high protein content and moderately high gluten strength. All experiments were planted with a plot drill in 18-cm rows at a rate of 323 seeds/m^2. Preplant fertilizer (N-P-K) was applied during the fall according to soil test recommendations and varied from 34 to 45 kg of N/ha, 29 to 40 kg of P/ha, and 56 to 111 kg of K/ha. Experiments were planted at Warsaw and Mt. Holly between October 22 and October 24 each year, while at Painter, plots were planted on October 19, 2001 and on November 26, 2002.

Spring nitrogen, based on standard split application management practices (Scharf and Alley 1993), was applied to the entire test area at growth stage GS 25 (45–62 kg of N/ha) and GS 30 (50–84 kg of N/ha) (Zadoks et al 1974). Late-season foliar N treatments consisted of 0, 22, 34, and 45 kg N/ha (0, 22, and 34 kg of N/ha at Mt. Holly in 2001) applied as dissolved urea solution at 420 L/ha at GS 37, GS 45, or GS 54. At the Warsaw site, each N treatment was applied to each cultivar at the specified growth stage (GS) resulting in applications that differed by calendar date. Harmony Extra (thifensulfuron methyl + tribenuron methyl) herbicide (35–38 g/ha) was applied to all experiments in early spring to control the weeds. Tilt (propiconazole) (280 g/ha) and Warrior-T (lambda-cyhalothrin) (175–350 g/ha) were applied when needed to control diseases and insect pests, respectively. Entire plots were harvested with a small plot combine, and grain subsamples taken from each plot were evaluated for grain volume weight and moisture using a Dickey-John GAC2000 grain sampler (DICKEY-john, Auburn, IL). Grain yields are reported on a 13.5% moisture basis. Experiments at Mt. Holly, Warsaw, and Painter were harvested within two days of one another each year, with harvest dates varying from June 13 to June 26 over the years tested.

Grain subsamples (1,000 g) were from the USDA Hard Winter Wheat Quality Lab, Manhattan, KS, for grain, flour, and milling and baking quality analysis. Single kernel wheat characteristics were determined by the Single Kernel Characterization System (SKCS) (Approved Method 55-31, AACC International 2000) developed by USDA/ARS/Grain Marketing and Production Research Center (Martin et al 1993). Each sample was visually inspected and all nonwheat particles were removed before processing. Approximately 300 kernels were processed through the SKCS to determine mean values of hardness index, weight (mg), and diameter (mm) of wheat kernels.

To measure near-infrared (NIR) kernel hardness, ≈18 g of whole kernels from each sample was ground in a cyclone sample mill (model MS, Udy Co., Fort Collins, CO) and passed through a 40-μm screen with a sample feed control rate of 1 g/sec. After a minimum of 3 hr, the ground sample was analyzed for hardness (NIRSystems 6500, Foss NIRSystems, Silver Spring, MD) (Norris et al 1989) and the resultant hardness scores (NIRHSC) were corrected for moisture content (Windham et al 1993). Wheat and flour protein (%N × 5.7) were determined by a nitrogen determinator (Leco, St. Joseph, MI) (Approved Method 46-30, AACC International 2000). Moisture and ash contents were determined by AACC Approved Methods 08-01 and 44-15A, respectively.

The wheat samples, tempered to constant moisture (16 and 15% moisture for hard winter and soft winter wheat, respectively), were milled on a Quadrumat Sr experimental mill (C.W. Brabender Co., Hackensack, NJ) according to AACC Approved Methods 26-10A and 26-50. Flour yield was determined as % of straight-grade flour. A standard sample was milled along with the experimental samples to check variation in flour yield day-to-day. Flour color was determined using a modified Agtron method on dry flour (AACC Approved Method 14-30). A mixogram for each of the flour samples (10 g, on a 14% moisture basis) was obtained using a 10-g mixograph (National Mfg. Co., Lincoln, NE) with optimum water adsorption (Finney and Shogren 1972). Mix time was visually determined from the mixogram. Mix time to peak dough development and mixing tolerance were determined by mixograph (AACC Approved Method 54-40). Corrected mixograph mix time is corrected based on protein content of flour. Corrected bake mix time was estimated at time of baking (AACC Approved Method 10-10B)

A straight-dough, 100-g pup-loaf bake test method was used to measure breadmaking properties for crumb grain score and loaf volume (AACC Approved Method 10-10B). Crumb grain of representative bread slices were graded from poor open grain (0) to outstanding closed grain (6), where scores between 3 and 4 are satisfactory according to the Wheat Quality Council, Hard Winter Wheat Testing Procedure (Wheat Quality Council 1995).

Data for grain yield and tissue N and S for Soissons were analyzed using the GLM procedure of the SAS Institute (Cary, NC) with S effect nested within replicates. Mean comparisons using a protected LSD test were made to separate treatment effects within each site year where F-tests indicated that significant differences existed ($P < 0.05$). The GLM procedure was also used to evaluate S application effects on kernel physical characteristics and milling and baking characteristics of all cultivars, and a protected LSD test was used to evaluate treatment differences. Single degree of freedom contrasts were used to evaluate the linear and quadratic effect of increasing N rate and to compare the simple effect of N application timing (GS 45 or 54) on grain yield, kernel physical characteristics, and milling and baking properties. The grain protein response to the N rate, with and without added S, was evaluated through regression. On the basis of differences observed in preliminary analysis of grain protein concentration among N and S treatments, only data from plots receiving sulfur (34 kg/ha) at GS 30 and late-season N treatments at GS 45 and GS 54 were reported subsequently for kernel physical and milling and baking characteristics. Data for grain, flour, and milling and baking characteristics of Heyne and Renwood 3260 were also analyzed using the GLM procedure and single degree of freedom contrasts.

Due to significant interactions involving N rate treatments, results for grain yield, kernel physical properties, and milling and baking properties are presented individually by year, location, and cultivar.

RESULTS AND DISCUSSION

Grain Yield of Soissons Wheat

Grain yields varied from 3.9 to 8.7 Mg/ha over experiments, yet a consistent relationship between late-season N application and grain yield was not observed for extremely high-yielding to low-yielding environments (Table I). Grain yield response to late-season N application was significant for GS 54 at Mt. Holly in 2001, GS 45 at Painter in 2002, and for GS 54 at Warsaw in 2003. This inconsistent yield response to late-season N is similar to that reported by Wuest and Cassman (1992) and Varga and Svecnjak (2006), where N was not a yield-limiting factor. Grain yield was lower where N was applied before GS 54 at both Painter (22 kg N/ha) and Warsaw (22 and 34 kg N/ha) in 2002. Woolfolk et al (2002) also noted a yield decrease when 22 kg of N/ha was applied as ammonium sulfate before anthesis. Over years and locations, application of late-season N up to 45 kg N/ha did not decrease grain yield and, therefore, late-season N applications can be made to enhance grain protein concentration without a detrimental effect on yield.

While Randall et al (1981) reported interaction effects between late-season N and S for grain yield, sulfur applied at 34 kg of S/ha at GS 30 had no effect on grain yield regardless of N treatment (Table II). Plant S levels were well above the critical level suggested by Randall et al (1990), which may explain the lack of yield response. Grain yield response to S and late-season N for the cultivars Heyne and Renwood 3260 was similar to that reported for Soissons (data not presented).

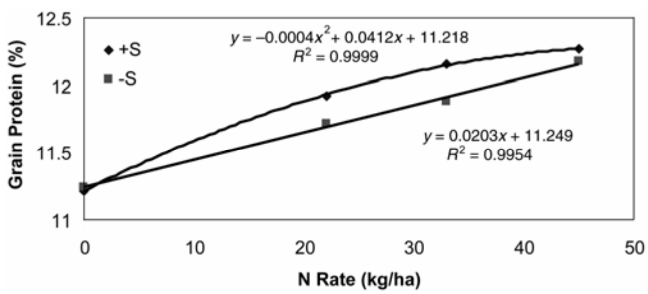

Fig. 1. Mean grain protein response of Soissons wheat to late-season N with and without S fertilization at Mt. Holly, Warsaw, and Painter, VA, during 2001–2003.

Grain Protein of Soissons Wheat

Grain protein concentration of Soissons wheat was not altered significantly with the addition of 34 kg of S/ha at GS 30 without late-season N. However, grain protein concentration increased an average of 0.2% when N was applied in conjunction with S (Fig. 1). Based on the quadratic response observed when both N and S were applied, a greater incremental advantage of S was observed at lower N rates (22 and 34 kg/ha). Late-season N alone increased grain protein concentration, but to a lesser extent than when the same N rate was applied to plots receiving S. This agrees with the findings of Hocking (1994) that remobilization of S from tissue to spring wheat grain was much lower than for N, indicating a continued need for S supply from outside the plant. Kratochvil et al (2005) also reported that late season N (GS 37–50) was necessary to achieve the highest grain protein.

TABLE I
Grain Yield Response (expressed as Mg/ha) of Soissons Winter Wheat to Late-Season Foliar N Applications[a]

	Mt. Holly 2001		Warsaw 2002		Warsaw 2003		Painter 2002		Painter 2003	
N Rate (kg/ha)	GS 45	GS 54	GS 45	GS 54	GS 45	GS 54	GS 45	GS 54	GS 45	GS 54
0	4.4	4.4	8.5	8.5	5.6	5.6	4.5	4.5	3.9	3.9
22	4.4	4.7	8.3	8.5	5.7	5.7	4.3	4.7	4.0	4.1
34	4.4	4.7	8.3	8.7	5.7	5.9	4.8	4.3	3.9	4.1
45	na[b]	na	8.5	8.1	5.8	5.9	5.1	4.8	3.9	4.1
Standard deviation	0.4	0.3	0.3	0.8	0.4	0.4	0.6	0.5	0.3	0.3
Contrasts					$P > F$					
N linear	ns[c]	*[d]	ns	ns	ns	*	ns	ns	ns	ns
N quad	ns	ns	ns	ns	ns	*	*	ns	ns	ns

[a] At three Virginia locations (Mt. Holly, Warsaw, Painter) for two growth stages (GS 45 and GS 54) according to Zadoks et al (1974).
[b] Not available.
[c] Not significant.
[d] * Significant at 5% probability.

TABLE II
Tissue N and S Content and Grain Yield of Soissons Winter Wheat After Nitrogen and Sulfur Fertilization[a]

	Tissue N (%)		Tissue S (%)		N:S Ratio		Grain Yield (Mg/ha)	
Location and Year	+S	–S	+S	–S	+S	–S	+S	–S
Mt. Holly 2001	4.0	4.2	0.40*[b]	0.33	10	13	na[c]	na
Warsaw 2002	4.6	4.5	0.34	0.33	14	13	8.3	8.3
Warsaw 2003	4.1	4.2	0.34*	0.30	12*	14	5.8	5.7
Painter 2002	4.6	4.5	0.33	0.31	14	15	4.7	4.5
Painter 2003	4.3	4.0	0.42*	0.38	10	11	4.2	3.9

[a] With and without sulfur (34 kg of S/ha) applied at growth stage GS 30 (Zadoks et al 1974).
[b] * Significant at 5% probability.
[c] Not available.

Tissue N and S Analysis of Soissons Wheat

The N:S ratio in Soissons was generally not significantly affected by S fertilization (Table II), which is similar to results reported by other researchers (Rasmussen et al 1975; Randall et al 1981). A standard ratio of about 1 part S to 15 parts N throughout the range of normal plant growth was reported by Flaete et al (2005). Unlike the concomitant increase of N in grain with added S, addition of S at GS 30 had no effect on tissue N content. Elevated tissue S concentration was observed in three of five experiments with an average increase of 0.04%.

Kernel, Flour, and Dough Response to S Fertilization

Kernel hardness was increased for Soissons at Mt. Holly in 2001 and kernel size was greater for Renwood 3260 with added S at Warsaw in 2003 (Table III). Otherwise, no consistent effect of S fertilization was observed for kernel physical characteristics in any cultivar.

Flour and Milling Characteristics of Wheat

Soissons. Single kernel hardness score was decreased by S fertilization at Mt. Holly in 2001 and increased at Painter in 2002 (Table IV). Flour yield was decreased at Mt. Holly in 2001 and Warsaw in 2002 when S was applied at GS 30. Wheat and flour protein of Soissons were increased at Mt. Holly in 2001 and Painter in 2002 and 2003 with application of S. Subsoil S levels at Painter and Mt. Holly are lower than at the Warsaw location, so this consistent response was not unexpected. Randall et al (1990) also found no response to S fertilization when soil supply was assumed adequate. Sulfur fertilization lowered flour ash at Mt. Holly in 2001. No differences due to S fertilization at Warsaw were noted for Heyne or Renwood 3260.

Dough Mixing and Baking Characteristics of Wheat

Soissons. Similar to grain and flour protein, water absorption was greater when S was applied at Mt. Holly in 2001 and Painter in 2002 and 2003 (Table V). This was also to be expected as protein quality and quantity affect water absorption. Mixing time was statistically increased in one site year with S fertilization, while correcting for flour protein content resulted in a significant effect of S in two site years. Sulfur increased loaf volume at Mt. Holly in 2001 and Painter in 2002.

Heyne and Renwood 3260. Sulfur addition had no effect on milling or baking properties for Renwood 3260. For Heyne, mix time, bake mix time, corrected bake mix time, and mixing tolerance were lower when S was added (Table V). Because of the tendency of S to increase grain and flour protein without a negative effect on grain yield or most end-use properties, all the kernel physical and milling and baking characteristics presented below are for those treatments that received S at GS 30 along with late-season N.

TABLE III
Physical Characteristics of Single Kernels from Soissons, Heyne, and Renwood 3260 Winter Wheat Cultivars After Nitrogen and Sulfur Fertilization[a]

Cultivars by Location and Year	Kernel Weight (mg)		Kernel Size (mm)		Kernel Hardness Score (0–100)	
	+S	–S	+S	–S	+S	–S
Soissons						
Mt. Holly 2001	37.9	38.0	2.63	2.64	57*[b]	56
Warsaw 2002	31.7	31.5	2.29	2.28	59	60
Warsaw 2003	29.9	29.6	2.24	2.22	50	49
Painter 2002	34.6	35.3	2.42	2.47	46	43
Painter 2003	32.2	31.8	2.30	2.29	52	51
Heyne						
Warsaw 2002	29.7	29.5	2.25	2.23	56	57
Warsaw 2003	33.2	33.8	2.42	2.41	41	42
Renwood 3260						
Warsaw 2002	26.4	25.9	2.06*	2.02	39	39
Warsaw 2003	31.9	31.5	2.31	2.29	26	26

[a] With and without sulfur (34 kg of S/ha) applied at growth stage GS 30 (Zadoks et al 1974).
[b] * Significant at 5% probability.

TABLE IV
Wheat Flour and Milling Characteristics of Soissons, Heyne, and Renwood 3260 Winter Wheat Cultivars After Nitrogen and Sulfur Fertilization[a]

Cultivars by Location/Year	NIRHSC[b] (0–100)		Flour Yield (%)		Flour Color[c]		Wheat Protein[d] (%)		Flour Protein[d] (%)		Flour Ash[d] (%)	
	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S
Soissons												
Mt. Holly 2001	51	55*[e]	72.6	73.0*	76	77	11.2*	10.9	9.9*	9.7	0.40	0.42*
Warsaw 2002	49	50	68.6	69.2*	75	75	12.3	12.2	10.8	10.7	0.45	0.46
Warsaw 2003	34	33	65.4	65.1	77	76	11.9	11.9	10.3	10.4	0.40	0.40
Painter 2002	34*	31	69.4	69.8	78	79	9.9*	9.0	8.3*	7.5	0.42	0.42
Painter 2003	44	43	69.3	69.2	77	76	11.2*	11.0	10.0*	9.8	0.44	0.44
Heyne												
Warsaw 2002	47	49	66.0	66.1	79	78	13.7	13.8	12.5	12.5	0.40	0.41
Warsaw 2003	26	27	63.5	62.1	81	81	11.7	11.6	10.0	9.9	0.32	0.32
Renwood 3260												
Warsaw 2002	22	22	64.7	65.3	78	78	13.6	13.6	11.8	11.9	0.39	0.39
Warsaw 2003	16	16	65.8	65.8	79	79	12.2	12.2	10.2	10.2	0.34	0.34

[a] With and without sulfur (34 kg of S/ha) applied at GS 30 growth stage (Zadoks et al 1974).
[b] NIR hardness score.
[c] Agtron color units.
[d] 14% moisture basis.
[e] Significant at 5% probability.

Kernel Physical Characteristics of Wheat

Soissons. A linear response of increasing kernel weight and size with higher N rate was observed only at Mt. Holly in 2001 (Table VI). Previous research (Varga and Svecnjak 2006) reported increased kernel weight with late-season N, but only when plants were supplied with below optimum N during prior growth stages, which may have been the case here. Kernel hardness increased with increasing N rate at Mt. Holly in 2001 (54.6–57.5), at Warsaw in 2002 (57.6–59.8), and at Painter in 2003 (49.5–52.7). Lack of a consistent response of kernel hardness to late-season N was reported previously by Altman et al (1983).

Heyne and Renwood 3260. Physical kernel characteristics of the hard white winter wheat cultivar Heyne were not affected by N application in either experimental year (Table VII). Kernel hardness of the SRW wheat cultivar Renwood 3260 at Warsaw in 2002 exhibited a linear increase (37 to 39.9 units) in response to increasing rates of late-season N (Table VII). No other kernel physical characteristics evaluated were significantly affected by N rate or application time.

Flour and Milling Characteristics of Wheat

Soissons. A linear response of NIR hardness score (NIRHSC) to increasing N rate was identified only at Mt. Holly in 2001 (Table VIII). Applying N at GS 54 increased NIRHSC by 1.53 units at Mt. Holly in 2001 and by 1.69 units at Painter in 2002 when compared with the N applied at GS 45. Flour yield was affected by late-season N application rate and timing only at the Mt. Holly location in 2001, where it increased by 0.66% with application of 34 kg of N/ha. This effect was greatest with the GS 45 application. Flour color showed a linear decrease (less white or bright) with increasing N application rate at Mt. Holly in 2001 and Painter in 2002. A significant linear increase in wheat protein concentration with increasing N rate was obtained in all site years, and in two of five site years, the GS 54 timing resulted in significantly higher protein values. This effect also has been documented in earlier studies with durum wheat (Garrido-Lestache et al 2005) and hard red winter wheat in the Mid-Atlantic region (Kratochvil et al 2005). On average, wheat protein concentration based on a uniform 14% moisture basis was 10.5, 11.1, 11.3, and 11.5% for the 0, 22, 34, and 45 kg of N/ha treatments, respectively. Flour protein concentrations increased proportionately, with average values of 9.2% with 0 N and 10.0% with 45 kg of N/ha. Two of the five site years had the highest flour protein concentrations with the GS 54 N application similar to the findings of Ayoub et al (1994). Flour ash was affected by N application timing in three site years with a slightly higher ash value associated with earlier (GS 45) N application in two site years.

Heyne and Renwood 3260. Kernel hardness (NIRHSC) and flour yields of Heyne and Renwood 3260 were not significantly affected by addition of late season N (Table IX). Flour color values for both cultivars decreased with application of late-season N in 2003 but differences were minor. A linear increase in both wheat and flour

TABLE V
Dough Mixing Characteristics of Soissons, Heyne, and Renwood 3260 Winter Wheat Cultivars After Nitrogen and Sulfur Fertilization[a]

Cultivars by Location/Year	Flour Protein (%) (14% moisture basis)		Water Absorption (%)		Mixing Time (min)		Corr Mixograph Mix Time (min)		Mixing Tolerance (0–7)	
	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S
Soissons										
Mt. Holly 2001	9.9*[b]	9.7	61*	60	5.47	5.31	4.25*	3.88	5.1	5.0
Warsaw 2002	10.8	10.7	62	62	4.72	4.71	4.06	4.00	5.0	5.0
Warsaw 2003	10.3	10.4	60	60	5.07	5.40	4.09	4.38	5.1	5.3
Painter 2002	8.3*	7.5	58*	57	5.29*	5.04	3.03*	2.39	5.0	4.7
Painter 2003	10.0*	9.8	60*	59	5.32	5.23	4.09	3.89	5.1	5.2
Heyne										
Warsaw 2002	12.5	12.5	64	64	3.90	3.77	3.89	3.77	2.9	3.6*
Warsaw 2003	10.0	9.9	61	61	3.19	3.73*	2.48*	2.85	3.0	3.6*
Renwood 3260										
Warsaw 2002	11.8	11.9	63	63	3.09	3.09	3.02	3.06	1.7	1.7
Warsaw 2003	10.2	10.2	61	61	3.07	3.19	2.44	2.53	2.8	2.8

[a] With and without sulfur (34 kg of S/ha) applied at GS 30 growth stage (Zadoks et al 1974).
[b] Significant at 5% probability.

TABLE V (*continued*)
Baking Characteristics of Soissons, Heyne, and Renwood 3260 Winter Wheat Cultivars After Nitrogen and Sulfur Fertilization[a]

Cultivars by Location/Year	Bake Water Absorption (%)		Bake Mix Time (min)		Corrected Bake Mix Time (min)		Loaf Volume (cm^3)		Crumb Grain Score (0–6)	
	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S
Soissons										
Mt. Holly 2001	62	62	7.52	7.40	5.67	5.42	706*[b]	695	2.7	2.8
Warsaw 2002	62	62	6.36	6.13	5.39	5.10	825	806	3.4	3.6
Warsaw 2003	57	57	6.99	6.61	5.27	5.39	766	773	2.8	2.8
Painter 2002	58	57	7.45	6.65	3.88	3.58	699*	666	3.4	3.1
Painter 2003	58	58	7.13	7.15	5.38	5.24	798	785	3.3	3.2
Heyne										
Warsaw 2002	63	62	4.71	5.31*	4.61	5.34*	916	926	3.8	3.5
Warsaw 2003	57	58*	3.81	4.38	2.95	3.32	761	757	2.9	2.8
Renwood 3260										
Warsaw 2002	59	59	3.35	3.40	3.21	3.33	914	905	3.1	3.3
Warsaw 2003	57	57	3.07	3.19	2.85	2.81	808	805	2.9	2.7

[a] With and without sulfur (34 kg of S/ha) applied at GS 30 growth stage (Zadoks et al 1974).
[b] Significant at 5% probability.

protein concentration (14% mb) in response to N rate was observed for the two cultivars in both years. Wheat protein concentration of Heyne increased by 0.75 and 1.38%, and flour protein increased by 0.76 and 1.12% over the control treatment with 34 and 45 kg of N/ha, respectively. Wheat protein concentration of Renwood 3260 increased by 0.45 and 0.48% and flour protein increased by 0.34 and 0.45% over the control treatment in 2002 and 2003, respectively, with 34 kg of N/ha. In three out of four comparisons, higher wheat and flour protein concentrations were obtained with N application at GS 54. Unlike Soissons, flour ash content of Heyne decreased with increasing N rate in 2003 and was lower for the GS 45 application, while flour ash content of Renwood 3260 was not affected by N rate but tended to be lower for the GS 54 N application.

TABLE VI
Single Kernel Physical Characteristics of Soissons Winter Wheat After Late-Season Foliar N Applications

	Soissons Kernels from Mt. Holly 2001		
N Rate (kg/ha)	Weight (mg)	Size (mm)	Hardness Score (0–100)
0	36.7	2.57	55
22	38.2	2.64	56
34	38.3	2.66	57
45	na[a]	na	na
Standard deviation	1.3	0.06	2
Growth stage[b]			
45	38.2	2.65	56
54	38.3	2.65	58
Contrasts		$P > F$	
N linear	0.0043	0.0013	0.0050
N quadratic	ns[c]	ns	ns
Growth stage	ns	ns	0.0006

[a] Not available.
[b] Zadoks et al (1974).
[c] Not significant.

Dough Mixing and Baking Characteristics of Wheat

Soissons. Water absorption increased linearly with increasing N rate at three of five experimental sites with an average increase of 2.5% when 34 kg of N/ha was added (Table X). Dough mixing time increased an average of 0.4 min in four of five site years for samples receiving 45 kg of N/ha, but this trend was significant only at Warsaw in 2002. Lack of a significant effect of increased late-season N on dough mixing time also was reported by Wooding et al (2000b), who found that addition of S along with N reduced the magnitude of increases in mix time. In the current study, mixing tolerance score decreased by one unit when 34 kg of N/ha was applied late-season at two site years, but optimum timing differed between these two responsive years. Applying 45 of kg N/ha resulted in an average loaf volume increase of 57.7 cm^3 when compared with the control treatment, and a significant linear trend for greater loaf volume with additional late-season N was noted in three of five site years. Loaf volume was reported to increase with higher late-season N supply by several researchers (Kosmolak and Crowle 1980; Ayoub et al 1994), who attribute this to an increase in total protein content.

TABLE VI (*continued*)
Single Kernel Physical Characteristics of Soissons Winter Wheat After Late-Season Foliar N Applications

	Soissons Kernels from Warsaw 2002			Soissons Kernels from Warsaw 2003		
N Rate (kg/ha)	Weight (mg)	Size (mm)	Hardness Score (0–100)	Weight (mg)	Size (mm)	Hardness Score (0–100)
0	30.8	2.23	58	29.3	2.22	50
22	31.8	2.31	60	29.7	2.21	50
34	31.6	2.28	60	30.0	2.25	49
45	31.7	2.29	60	29.9	2.25	49
Standard deviation	1.4	0.07	2	0.6	0.04	1
Growth stage[a]						
45	31.6	2.29	60	29.7	2.23	49
54	31.8	2.30	59	30.0	2.24	49
Contrasts			$P > F$			
N linear	ns[b]	ns	0.0908	ns	ns	ns
N quadratic	ns	ns	ns	ns	ns	ns
Growth stage	ns	ns	ns	ns	ns	ns

[a] Zadoks et al (1974).
[b] Not significant.

TABLE VI (*continued*)
Single Kernel Physical Characteristics of Soissons Winter Wheat After Late-Season Foliar N Applications

	Soissons Kernels from Painter 2002			Soissons Kernels from Painter 2003		
N Rate (kg/ha)	Weight (mg)	Size (mm)	Hardness Score (0–100)	Weight (mg)	Size (mm)	Hardness Score (0–100)
0	34.3	2.42	45	32.7	2.34	49
22	34.3	2.41	44	32.4	2.32	51
34	34.6	2.43	44	32.1	2.31	53
45	36.2	2.50	45	31.1	2.25	51
Standard deviation	1.3	0.05	1	0.7	0.00	2
Growth stage[a]						
45	35.1	2.45	45	31.7	2.28	51
54	35.0	2.45	44	32.1	2.29	52
Contrasts			$P > F$			
N linear	ns[b]	ns	ns	ns	ns	0.0544
N quadratic	ns	ns	ns	0.0973	ns	ns
Growth stage	ns	ns	ns	0.0566	0.0520	ns

[a] Zadoks et al (1974).
[b] Not significant.

Late-season N application did not have a significant effect on bread crumb grain score in any site year.

Heyne and Renwood 3260. Water absorption increased linearly with increasing N rate for Heyne in both years and for Renwood 3260 in 2002 (Table XI). Application of 34 kg of N/ha resulted in a 2% average increase in water absorption over the 0 N control. While late-season N applications did not affect dough mixing properties of the hard white winter wheat cultivar Heyne, a linear response of mixing time to increasing N rates was observed for the SRWW cultivar Renwood 3260 in both years with an average increase of 0.6 min associated with treatment of 34 kg of N/ha.

Late-season N application increased bread loaf volume (41–66 cm^3) in both cultivars in 2003, while no significant response was obtained in 2002. Loaf volume scores for control treatments of both cultivars were higher (892 cm^3 for Heyne and 905 cm^3 for Renwood 3260) in 2002 relative to 2003, and may explain the lack of response to additional N. While crumb grain scores of the two cultivars exhibited a linear response to N application in one of the two years, addition of late-season N decreased crumb grain scores of Heyne and increased those of Renwood 3260 in 2002.

CONCLUSIONS

Three markedly diverse wheat cultivars that had distinct origins, genetic composition, and end-use quality characteristics were included in these studies and the response to N and S management was determined for each. Locations with different soil type profiles were also included to assess the potential effect of soil type and mineral holding capacity on response of wheat to application of additional N and S. Late-season foliar N applications up to 45 kg of N/ha did not result in consistent increases in wheat grain yield among the three cultivars, nor did they reduce grain yields of any cultivar. Similarly, application of 34 kg of S/ha at GS 30 did not affect grain yield of any cultivar. These results indicate that application of additional S or late-season N to enhance grain protein and baking quality of bread wheat grown in humid, high-rainfall regions can be implemented without adverse effects on grain yield.

In contrast to yield, grain and flour protein concentration of all three cultivars were consistently increased with the application of late-season foliar N applications up to 34–45 kg of N/ha. While application of 34 kg of S/ha at GS 30 in experiments conducted at Warsaw, VA, did not have a significant effect on grain yield or protein concentration of any cultivar, application of S to Soissons wheat in experiments conducted at Mt. Holly and Painter, VA, resulted in a significant increase in grain protein concentration when applied in conjunction with late-season N. The contrast in response of Soissons to S application at these two locations likely is due to residual S and differences in the mineral holding capacity of the soils at these three locations. The subsoil at Warsaw has a significant amount of clay that maintains more available sulfur than the subsoil at Painter, which is predominantly sandy. Growth stage (GS45 vs. GS54) of late-season N application generally did not differ significantly as to effect on grain, flour, and bread quality characteristics, which affords producers a broader window of opportunity for late-season N applications.

TABLE VII
Single Kernel Physical Characteristics of Heyne Winter Wheat After Late-Season Foliar N Applications

	Heyne Kernels from Warsaw 2002			Heyne Kernels from Warsaw 2003		
N Rate (kg/ha)	Weight (mg)	Size (mm)	Hardness Score (0–100)	Weight (mg)	Size (mm)	Hardness Score (0–100)
0	28.5	2.19	58	32.9	2.41	41
22	29.5	2.25	56	33.1	2.41	41
34	30.0	2.25	56	33.5	2.44	41
45	29.8	2.26	57	32.7	2.40	42
Standard deviation	1.0	0.06	2	1.0	0.03	1
Growth stage[a]						
45	29.6	2.24	57	32.8	2.40	41
54	29.9	2.26	56	33.4	2.43	42
Contrasts	$P > F$					
N linear	ns[b]	ns	ns	ns	ns	ns
N quadratic	ns	ns	ns	ns	ns	ns
Growth stage	ns	ns	ns	ns	ns	ns

[a] Zadoks et al (1974).
[b] Not significant.

TABLE VII (*continued*)
Single Kernel Physical Characteristics of Renwood 3260 Winter Wheat After Late-Season Foliar N Applications

	Renwood 3260 Kernels from Warsaw 2002			Renwood 3260 Kernels from Warsaw 2003		
N Rate (kg/ha)	Weight (mg)	Size (mm)	Hardness Score (0–100)	Weight (mg)	Size (mm)	Hardness Score (0–100)
0	26.0	2.03	37	31.4	2.27	24
22	26.3	2.05	39	31.1	2.28	26
34	26.1	2.03	40	31.8	2.30	26
45	26.2	2.04	40	32.3	2.35	27
Standard deviation	0.1	0.05	1	0.8	0.04	1
Growth stage[a]						
45	25.6	2.06	39	31.9	2.31	26
54	25.9	2.02	40	31.6	2.30	27
Contrasts	$P > F$					
N linear	ns[b]	ns	0.0806	ns	ns	ns
N quadratic	ns	ns	ns	ns	ns	ns
Growth stage	ns	ns	0.0708	ns	ns	ns

[a] Zadoks et al (1974).
[b] Not significant.

TABLE VIII
Wheat Flour and Milling Characteristics of Soissons Winter Wheat at Three Locations, Two Growth Stages, and Three Growing Years After Late-Season Foliar N Applications

N Rate (kg/ha) by Location/Cultivar	NIRHSC[a] (0–100)	Flour Yield (%)	Flour Color[b]	Wheat Protein[c] (%)	Flour Protein[c] (%)	Flour Ash[c] (%)
Mt. Holly 2001						
0	50	72.3	77	10.3	9.2	0.42
22	53	72.9	76	11.0	9.8	0.41
34	55	73.0	76	11.4	10.1	0.40
Growth stage[d]						
45	53	73.0	76	10.9	9.7	0.41
54	55	72.8	75	11.4	10.1	0.40
Contrasts			*P* > *F*			
N linear	<0.0001	<0.0001	0.0305	<0.0001	<0.0001	0.0042
N quadratic	ns[e]	0.0575	ns	ns	ns	ns
Growth stage	<0.0001	0.0004	0.0043	<0.0001	<0.0001	0.0004
Warsaw 2002						
0	49	68.6	77	11.7	10.2	0.44
22	48	68.8	76	12.1	10.6	0.44
34	49	69.0	74	12.3	10.9	0.48
45	51	68.9	75	12.5	10.9	0.47
Growth stage						
45	49	68.9	75	12.3	10.7	0.45
54	50	69.0	75	12.2	10.8	0.47
Contrasts			*P* > *F*			
N linear	ns	ns	ns	0.0348	0.0222	0.0150
N quadratic	ns	ns	ns	ns	ns	ns
Growth stage	ns	ns	ns	0.0206	0.0259	0.0290
Warsaw 2003						
0	36	65.3	77	11.3	9.8	0.42
22	33	65.1	76	11.9	10.3	0.41
34	34	65.3	77	11.9	10.4	0.41
45	31	65.3	77	12.1	10.5	0.39
Growth stage						
45	33	64.9	76	11.9	10.3	0.41
54	33	65.5	77	12.1	10.5	0.39
Contrasts			*P* > *F*			
N linear	ns	ns	ns	0.0119	0.0129	ns
N quadratic	ns	ns	ns	ns	ns	ns
Growth stage	ns	ns	ns	0.0140	0.0154	0.0582
Painter 2002						
0	29	69.5	80	8.9	7.4	0.42
22	31	69.7	79	9.3	7.7	0.42
34	32	69.4	78	9.6	8.1	0.43
45	36	69.8	79	9.8	8.3	0.41
Growth stage						
45	32	70.1	78	9.6	8.0	0.41
54	34	69.2	79	9.6	8.0	0.43
Contrasts			*P* > *F*			
N linear	ns	ns	0.0904	0.0079	0.0030	ns
N quadratic	ns	ns	ns	0.0053	0.0040	0.0390
Growth stage	0.0602	ns	ns	ns	ns	ns
Painter 2003						
0	45	69.7	77	10.4	9.3	0.45
22	42	69.5	77	11.1	9.7	0.44
34	44	69.5	76	11.3	10.0	0.44
45	43	68.7	77	11.5	10.2	0.43
Growth stage						
45	43	69.3	77	11.3	10.0	0.43
54	43	69.0	76	11.3	10.0	0.44
Contrasts			*P* > *F*			
N linear	ns	ns	ns	<0.0001	<0.0001	ns
N quadratic	0.0238	ns	ns	0.0002	<0.0001	ns
Growth stage	ns	ns	ns	ns	ns	ns

[a] NIR hardness score.
[b] Agtron color units.
[c] 14% moisture basis.
[d] Zadoks et al (1974).
[e] Not significant.

Environmental effects, including wheat production site and the underlying differences in soil type, precipitation, and other factors, had a significant influence on the magnitude of response in Soissons wheat to application of additional S and late-season N. Average grain protein concentration of Soissons was consistently lower in both the 2002 and 2003 tests at Painter (9.38 and 11.05%) than at Warsaw (12.15 and 11.80%), respectively, even though differences in tissue N and S content and N:S ratios were not markedly different (Tables II and VIII).

While this finding is not surprising considering that it is well documented that that environment has a major effect on grain protein concentration, it does suggest that recommended fertility management protocols including the application of additional S or late-season N to boost grain protein in bread wheat need to be site-specific.

Increases in grain protein concentration with application of 45 kg of N/ha vs. the control treatment at Warsaw in 2002 and 2003 varied from 0.75 to 1.38% for the hard white winter wheat HWWW

TABLE IX
Wheat Flour and Milling Characteristics of Heyne and Renwood 3260 Winter Wheat at Three Locations, Two Growth Stages, and Three Growing Years After Late-Season Foliar N Applications

N Rate (kg/ha) by Location/Cultivar	NIRHSC[a] (0–100)	Flour Yield (%)	Flour Color[b]	Wheat Protein[c] (%)	Flour Protein[c] (%)	Flour Ash[c] (%)
Warsaw 2002 Heyne						
0	48	65.9	78	13.1	11.9	0.41
22	48	66.2	79	13.7	12.4	0.41
34	48	65.9	78	13.9	12.5	0.41
45	48	66.2	79	13.9	12.7	0.40
Growth stage[d]						
45	48	66.0	78	14.0	12.7	0.40
54	47	66.1	79	13.7	12.4	0.41
Contrasts			$P > F$			
N linear	ns[e]	ns	ns	0.0004	0.0068	ns
N quadratic	ns	0.0241	ns	0.0018	0.0890	ns
Growth stage	ns	0.0331	ns	0.0018	0.0330	ns
Warsaw 2002 Renwood 3260						
0	21	65.9	79	13.3	11.6	0.41
22	22	65.7	78	13.6	11.8	0.39
34	23	64.4	78	13.8	11.9	0.40
45	23	64.3	79	13.7	11.9	0.38
Growth stage						
45	23	65.2	78	13.5	11.7	0.40
54	22	64.4	78	13.8	12.0	0.37
Contrasts			$P > F$			
N linear	ns	ns	ns	0.0821	0.0590	ns
N quadratic	ns	ns	ns	ns	ns	ns
Growth stage	ns	ns	ns	0.0821	0.0417	0.0298
Warsaw 2003 Heyne						
0	27	63.6	82	10.6	9.2	0.34
22	27	63.0	81	11.6	9.9	0.32
34	27	62.3	81	11.8	10.1	0.32
45	26	62.7	81	11.9	10.3	0.32
Growth stage						
45	27	63.3	81	11.7	10.0	0.31
54	26	62.0	80	11.9	10.2	0.32
Contrasts			$P > F$			
N linear	ns	ns	0.0833	<0.0001	0.0002	0.0192
N quadratic	ns	ns	ns	0.0001	0.0005	0.0369
Growth stage	ns	ns	0.0833	<0.0001	<0.0001	0.0345
Warsaw 2003 Renwood 3260						
0	15	65.4	81	11.8	9.8	0.34
22	16	65.5	79	12.1	10.1	0.35
34	16	66.4	79	12.2	10.3	0.35
45	17	65.7	79	12.5	10.5	0.34
Growth stage						
45	16	66.0	79	12.2	10.2	0.35
54	16	65.8	79	12.3	10.4	0.34
Contrasts			$P > F$			
N linear	ns	ns	0.0050	0.0201	0.0286	ns
N quadratic	ns	ns	ns	ns	ns	ns
Growth stage	ns	ns	0.0054	0.0201	0.0292	ns

[a] NIR hardness score.
[b] Agtron color units.
[c] 14% moisture basis.
[d] Zadoks et al (1974).
[e] Not significant.

TABLE X
Dough Mixing and Baking Characteristics of Soissons Winter Wheat at Three Locations, Two Growth Stages, and Three Growing Years After Late-Season Foliar N Applications (2001–2003)

N Rate (kg/ha) by Location/Year	Flour Protein[a] (%)	Water Abs (%)	Mixing Time (min)	Corr Mixo-graph Mix Time (min)	Mixing Tolerance Score (0-7)	Bake Water Abs (%)	Bake Mix Time (min)	Corr Bake Mix Time (min)	Loaf Vol (cm^3)	Crumb Grain Score (0-6)
Mt. Holly 2001										
0	9.2	56	3.83	3.71	5.1	61	7.63	5.26	670	2.7
22	9.8	60	4.02	4.21	5.1	62	7.56	5.51	707	2.9
34	10.1	61	4.10	4.29	4.9	62	7.49	5.73	708	2.6
Growth stage[b]										
45	9.7	60	3.82	4.21	5.0	62	7.56	5.29	704	2.7
54	10.1	61	4.31	4.29	5.1	62	7.49	5.95	711	2.8
Contrasts					$P > F$					
N linear	<0.0001	0.0002	ns[c]	ns	ns	0.0876	0.0981	0.0976	0.0001	ns
N quadratic	ns	ns	ns	ns	ns	0.0964	ns	ns	0.0141	0.0758
Growth stage	<0.0001	0.0024	0.0250	0.0310	ns	0.0083	ns	0.0182	<0.0001	ns
Warsaw 2002										
0	10.2	61	3.55	3.58	5.0	62	6.00	4.64	805	3.8
22	10.6	62	3.78	3.81	5.0	62	6.00	4.92	813	3.4
34	10.9	62	4.20	4.37	5.0	63	6.75	5.42	820	3.6
45	10.9	61	4.11	4.10	5.0	62	6.38	5.71	819	3.5
Growth stage										
45	10.7	62	4.14	4.13	5.0	62	6.50	5.51	822	3.6
54	10.8	62	3.92	4.00	5.0	62	6.25	5.19	813	3.4
Contrasts					$P > F$					
N linear	0.0222	ns	0.0163	0.0203	ns	ns	ns	ns	ns	ns
N quadratic	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Growth stage	0.0259	ns	0.0490	0.0411	ns	ns	ns	ns	ns	ns
Warsaw 2003										
0	9.8	59	4.31	4.22	6.0	57	6.13	5.00	710	2.0
22	10.3	60	4.25	3.91	5.3	58	6.75	5.33	779	2.7
34	10.4	60	4.17	4.29	5.0	57	7.00	5.51	769	2.5
45	10.5	61	4.29	4.08	5.0	57	6.32	5.33	791	3.6
Growth stage										
45	10.3	60	4.14	3.95	5.2	58	6.50	5.02	785	2.8
54	10.5	61	4.33	4.24	5.0	57	6.88	5.76	774	3.1
Contrasts					$P > F$					
N linear	0.0129	0.0152	ns	ns	0.005	ns	ns	ns	0.0101	ns
N quadratic	ns	ns	ns	ns	ns	ns	ns	ns	0.0071	ns
Growth stage	0.0154	ns	ns	ns	0.005	ns	ns	ns	0.0074	ns
Painter 2002										
0	7.4	56	2.26	2.63	4.5	57	7.00	4.09	683	3.3
22	7.7	57	2.43	2.87	4.8	59	6.94	3.41	678	3.4
34	8.1	57	2.92	3.19	5.0	57	6.50	3.74	679	2.7
45	8.3	58	2.78	3.04	5.0	58	6.50	3.86	693	3.8
Growth stage										
45	8.0	57	2.72	3.00	5.0	58	6.46	3.70	683	3.3
54	8.0	57	2.70	3.06	4.8	58	6.83	3.64	683	3.3
Contrasts					$P > F$					
N linear	0.0030	0.0033	ns	ns	ns	ns	0.0062	0.0964	ns	ns
N quadratic	0.0040	0.0042	0.0557	0.0374	ns	ns	0.0746	ns	ns	ns
Growth stage	ns	ns	ns	ns	ns	ns	0.0048	ns	ns	ns
Painter 2003										
0	9.3	59	3.95	3.94	6.0	58	7.00	4.84	743	2.8
22	9.7	59	3.69	3.86	5.0	58	7.19	5.22	796	3.1
34	10.0	60	3.92	4.13	5.0	58	7.44	5.41	786	3.5
45	10.2	60	4.35	4.28	5.3	57	6.75	5.55	816	3.4
Growth stage										
45	10.0	60	3.98	4.14	5.0	58	7.17	5.34	788	3.4
54	10.0	60	4.00	4.03	5.2	57	7.08	5.44	812	3.3
Contrasts					$P > F$					
N linear	<0.0001	ns	ns	ns	0.005	ns	ns	ns	0.0211	ns
N quadratic	<0.0001	ns	ns	ns	0.003	ns	ns	ns	ns	ns
Growth stage	ns	ns	ns	ns	0.005	ns	ns	ns	0.0119	ns

[a] 14% moisture basis
[b] Zadoks et al (1974).
[c] Not significant.

cultivar Heyne, 0.83 to 0.85% for the French bread wheat cultivar Soissons, and 0.43 to 0.70% for the soft red winter wheat cultivar Renwood 3260.

This indicates that the inherent genetic potential and composition of a given cultivar has a major impact on the magnitude and biological significance of the effects that a fertility management regime likely will have on grain, flour, and end-use quality characteristics. In a majority of site years, application of late-season N did not have a significant or consistent effect on kernel hardness, flour yield, ash content, or crumb grain of the three cultivars. Flour color scores were slightly lower for Soissons in two of the five site years and for Heyne and Renwood 3260 at Warsaw in 2003 when late-season N was applied.

Increased water absorption with late-season N application was noted in six of ten instances, indicating that breadmaking quality may also be improved. In two of the five site years, mixing tolerance scores for Soissons exhibited a linear decrease with the increased late-season N treatment. In contrast, application of late-

TABLE XI
Dough Mixing and Baking Characteristics of Heyne and Renwood 3260 Winter Wheat at Three Locations, Two Growth Stages, and Three Growing Years After Late-Season Foliar N Applications

N Rate (kg/ha) by Location	Flour Protein[a] (%)	Water Abs (%)	Mixing Time (min)	Corr Mixograph Mix Time (min)	Mixing Tolerance Score (0–7)	Bake Water Abs (%)	Bake Mix Time (min)	Corr Bake Mix Time (min)	Loaf Vol (cm^3)	Crumb Grain Score (0–6)
Warsaw 2002 Heyne										
0	11.9	62	3.59	3.18	3.0	60	4.13	4.77	893	4.3
22	12.4	63	3.91	3.82	2.8	62	4.38	4.72	894	3.6
34	12.5	64	3.82	3.82	3.3	62	4.50	4.81	928	3.5
45	12.7	64	3.78	3.69	3.8	63	5.25	5.50	956	3.6
Growth stage[b]										
45	12.7	64	4.00	3.92	3.2	63	4.75	5.15	931	3.3
54	12.4	64	3.67	3.63	3.3	63	4.67	4.88	921	3.8
Contrasts	*P* > *F*									
N linear	0.0068	0.0054	ns[c]	ns	ns	ns	ns	ns	ns	0.0387
N quadratic	0.0890	0.0091	ns	ns	ns	ns	0.072	0.0737	ns	ns
Growth stage	0.0330	ns	ns	ns	ns	ns	ns	ns	ns	0.0592
Warsaw 2002 Renwood 3260										
0	11.6	61	2.56	2.57	1.0	59	3.25	3.10	905	2.8
22	11.8	62	2.86	2.89	1.5	58	3.13	3.19	906	3.4
34	11.9	63	3.11	3.12	2.0	59	3.32	3.42	920	3.4
45	11.9	63	3.15	3.05	2.0	59	3.50	3.30	904	3.1
Growth stage										
45	11.7	62	2.92	2.92	1.7	59	3.38	3.28	905	3.1
54	12.0	63	3.16	3.11	2.0	58	3.25	3.32	915	3.5
Contrasts	*P* > *F*									
N linear	0.0590	<0.0001	0.0043	0.0072	na[d]	ns	ns	0.0906	ns	0.0177
N quadratic	ns	ns	ns	0.0052	na	ns	ns	ns	ns	ns
Growth stage	0.0417	0.0031	0.0029	0.0029	na	ns	ns	ns	ns	0.0356
Warsaw 2003 Heyne										
0	9.2	59	2.65	2.39	3.5	58	4.4	3.06	715	2.8
22	9.9	61	2.78	2.49	3.5	58	4.1	3.20	763	2.9
34	10.1	61	2.49	2.34	3.0	58	3.8	3.21	756	2.9
45	10.3	62	2.71	2.60	3.3	57	3.6	3.04	781	2.9
Growth stage										
45	10.0	61	2.52	2.30	3.2	57	3.6	3.15	760	3.0
54	10.2	61	2.80	2.65	3.3	58	4.0	3.15	773	2.8
Contrasts	*P* > *F*									
N linear	0.0002	0.0001	ns	ns	ns	ns	ns	ns	0.0116	ns
N quadratic	0.0005	0.0022	ns	ns	ns	0.0167	ns	ns	0.0795	ns
Growth stage	<0.0001	ns	ns	ns	ns	0.0933	ns	ns	0.0051	ns
Warsaw 2003 Renwood 3260										
0	9.8	61	1.89	1.92	2.0	56	3.50	2.58	760	2.5
22	10.1	61	2.52	2.45	2.0	57	3.63	2.76	816	3.0
34	10.3	61	2.42	2.31	2.0	57	3.57	2.79	808	2.7
45	10.5	61	2.51	2.57	3.0	57	3.57	2.94	815	2.7
Growth stage										
45	10.2	61	2.42	2.40	2.3	57	3.63	2.86	812	2.7
54	10.4	60	2.55	2.48	2.3	57	3.54	2.80	814	2.9
Contrasts	*P* > *F*									
N linear	0.0286	ns	0.0078	0.0079	ns	ns	ns	0.0002	0.0162	ns
N quadratic	ns	0.0322	0.0377	0.0310	ns	ns	0.0039	0.0006	0.0298	ns
Growth stage	0.0292	ns	0.0053	ns	ns	ns	ns	<0.0001	0.0097	ns

[a] 14% moisture basis.
[b] Zadoks et al (1974).
[c] Not significant.
[d] Not available.

season N consistently increased the dough mixing time and bake mix time of the SRWW cultivar Renwood 3260, which potentially would improve its breadmaking properties because mix times without the late season N averaged only 2.23 min. Late-season N application, as observed for grain and flour protein concentration, generally increased loaf volume with significant effects observed for Soissons in three of five site years and for Heyne and Renwood 3260 in one of two test years. Overall, application of late-season N tended to affect the dough mixing and baking properties of the SRWW cultivar Renwood 3260 to a greater extent than those of the HRWW cultivar Heyne, which inherently possesses good bread quality characteristics. The French bread wheat cultivar Soissons inherently has moderately low grain protein concentration, yet has considerably strong gluten. While late-season N applications had little effect on Soissons dough mixing properties, grain and flour protein concentrations and loaf volume were improved significantly.

In summary, application of 34–45 kg of N/ha between GS 45 and 54 to winter bread wheat cultivars grown in humid, high-rainfall areas likely will result in consistent increases in grain and flour protein concentration as well as increased water absorption and improvements in bread loaf volume. Availability of S and a desirable N:S ratio is critical when considering the positive interaction between N and S on grain protein quantity and quality.

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[Received January 2, 2007. Accepted March 28, 2007.]