In-Season Application of Nitrogen and Sulfur in Winter Wheat

Jagmandeep Dhillon, Sulochana Dhital, Tyler Lynch, Bruno Figueiredo, Peter Omara, and W. R. Raun*

Core Ideas

- Decreased atmospheric deposition has led to increased S consumption in winter wheat.
- Sulfur did not increase yield or grain N concentration at any site.
- Use of recommended soil testing guides are encouraged.

Dep. of Plant and Soil Sciences, Oklahoma State Univ., Stillwater, OK 74078.

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*Corresponding author (bill.raun@okstate.edu).

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ABSTRACT

Decreased atmospheric S deposition in the past 20 yr has led to increased S fertilizer consumption in winter wheat (*Triticum aestivum* L.). Producers often apply S without any soil test information. Experiments were conducted at Lahoma, Lake Carl Blackwell, and Perkins, OK (2011–2013) to assess the effect of N and S applied preplant and foliar on grain yield and grain N for winter wheat. In 2011–2012, urea ammonium nitrate (UAN) was applied preplant at rates of 40 and 80 kg N ha^{-1} additionally; UAN and urea-triazone (NSURE) were foliar-applied at rates of 10 and 20 kg N ha^{-1}. Sulfur was foliar-applied as gypsum ($CaSO_4{\cdot}2H_2O$) at 6 kg S ha^{-1}. In 2013, trials were altered to apply 40 kg N ha^{-1} as UAN preplant, and 20 kg N ha^{-1} foliar-applied. Gypsum rates were adjusted at 0, 3, and 6 kg S ha^{-1} preplant, and S (MAX-IN-S) at 3 and 6 kg S ha^{-1} was foliar-applied. Sulfur did not increase grain yield or grain N concentration at any site. The interaction between foliar S and N and preplant S and N was not significant. Sulfur fertilizer application is less likely to benefit this region unless low levels of soil test S are identified before planting. Use of recommended soil-testing guides are encouraged. Although S applications are encouraged commercially, no response was observed in these trials, and all were on sites where soil organic carbon was low (<8.5 g kg^{-1}), where the possibility of seeing S deficiency was greater.

Abbreviations: ATV, all-terrain vehicle; GS, glutamine synthetase; NR, nitrate reductase; UAN, urea ammonium nitrate.

Adequate and timely fertilization is essential for managing small grain production systems to maximize grain yields (Raun et al., 2002). Crops have different nutritional requirements, depending on the availability of specific limiting nutrients in the growing environment. Based on the specific nutrient availability, some nutrients are more frequently required than others are.

Sulfur and N are essential elements for plant growth and development, their assimilation in plants are similar, and both are critical components in the structure of the plant enzymes (Shewry and Tatham, 1997). Nitrogen concentrations in wheat (*Triticum aestivum* L.) shoots range from 1.8 to 2.6% and 1.6 to 2.0% in grain. Sulfur concentration is much lower, with 0.15 to 1.4% in shoots and 0.1 to 0.2% in grain (Duncan et al., 2018). For total plant N, protein accounts for almost 80% and chlorophyll generally accounts for less than 10% (Imsande, 1998). Sulfur is a component of methionine and cysteine, two important S-containing amino acids that account for 21 and 27% S, respectively (Jordan and Ensminger, 1959). Sulfur and N are constituents of protein and maintain a 1:15 to 1:20 (S/N) ratio. As N and S are essential constituents of wheat protein, optimum grain yield requires an adequate amount of both nutrients (Tea et al., 2007). Furthermore, S and N are both mobile in the soil, and highly susceptible to leaching in high rainfall areas.

Timms et al. (1981) suggested that the balance between N and S changes and insufficient S leads to poor grain development when the crop needs a large amount of N late in the season. Sulfur deficiency in cereal crops was first reported in Scotland (Scott et al., 1984). The essential role of S for plant growth was recognized much earlier (Jordan and Ensminger, 1959).

Plants experiencing a deficiency of N and S result in a similar yellow discoloration, but S deficiency symptoms are visible in the younger leaves, unlike N that shows up in the older, lower leaves. The deficiency of these nutrients reduces the amount of chlorophyll inducing different mechanisms; therefore, it could be difficult to visually differentiate between S and N deficiencies (Imsande, 1998). Reports from around the globe noted that over the last few decades S deficiencies has increased in areas previously sufficient in S (Scherer, 2009). The possible reasons behind the S deficiency could be a reduction in S fertilizer use, reduced use of fungicides/pesticides containing S, and reduced industrial S emissions since 1980 (Smith et al., 2011). In many areas, the reduced S emissions have directly decreased the atmospheric S dioxide concentrations and thereby decreased input to crops.

The requirements of S vary for different crops. In a greenhouse experiment, Holford (1971) found that cereals like wheat and oat (*Avena sativa* L.) were more sensitive to S deficiency than legumes, and require more S for maximum dry matter production. The demand for S is higher for oilseed rape (*Brassica napus* L.) as they use S for glucosinolate, an S-containing compound that imparts a pungent odor in plants of the Brassicaceae family (Zhao et al., 1993). Wheat generally requires lower quantities of S, with roughly 20 kg S ha^{-1} needed to produce a grain yield of 8 Mg ha^{-1} (McGrath et al., 1996). Additionally, sufficient levels of S results in maximum N response (Hu and Sparks, 1992).

Zhang and Raun (2006) noted that for winter wheat and other legumes in Oklahoma, an N/S ratio of 20:1 was desirable. Shahsavani and Gholani (2008) suggested that cereal crops require 15 to 20 kg S ha^{-1}. Deep sandy soils receiving lower amounts of S via precipitation together with lower S fertilizer applications may need additional S when cereal crops are grown. Harper (2015) studied S content in Oklahoma rainfall for 15 yr (1927–1942). The average amount of S was 9.8 kg ha^{-1}. This is lower than the results from Johnson and Zhang (2003), noting that this was 22.4 kg S ha^{-1} through annual precipitation. Other work by LaRuffa et al. (1999) showed that winter wheat studies in Oklahoma, specifically Perkins and Carrier, which have deep sandy soils, showed an S response where organic C levels were low. Similar results by Khan et al. (2006) reported an S response in maize (*Zea mays* L.), and also on soils low in organic matter (<1.2%).

The S requirement for canola (*Brassica napus* L.) is understood to be higher than other crops, and research in Oklahoma did not show any response between sources and rate of S for two different cultivars (HyClass 154 and DKW 47-15) over growing seasons (Barrett et al., 2012). This research was conducted at Perkins, OK, on a sandy soil where leaching could remove mobile nutrients like N and S.

It has been suggested that foliar-applied N and S, have synergistic effects on increasing their assimilation in grain and can improve bread-baking qualities. Sulfur deficiency will reduce N absorption, affecting protein content and affecting flour quality (Tao et al., 2018). Protein content in wheat flour was reported to be significantly affected by the activity of nitrate reductase (NR) and glutamine synthetase (GS) (Tao et al., 2018). Sulfur fertilization tends to increase NR and GS activity in flag leaves, thus affecting the content of protein components (Geng et al., 2016). Sulfur nutrition in wheat helps to improve baking quality of wheat flour (Thomason et al., 2001). It has been established that the disulfide bond of S for wheat proteins are important for determining bread-making properties of wheat flour (Shewry and Tatham, 1997). Dough extensibility is important for manual shaping of bakery products. Sulfur deficiency can limit dough extensibility and increase toughness (Kettlewell et al., 1998). The formation of lower quality proteins in S deficient situations increases the elasticity and decreases the extensibility (Wrigley et al., 1984), while severe S deficiency can significantly decrease the loaf volume.

Although the evidence of wheat responses to S exists in previous research in some locations of Oklahoma, current research is not sufficient to show that S application in Oklahoma wheat is required to increase the production and end-use quality. However, S application is being promoted among wheat growers without considering soil test S levels. The objective of this study was to evaluate the need for S application along with N for winter wheat in Oklahoma, considering the growing concerns for decreased atmospheric S. Another objective was to assess whether in-season foliar applications were better in comparison to preplant treatments.

MATERIALS AND METHODS

Field trials were established at two locations, Lake Carl Blackwell and Lahoma, in the fall of 2011 and 2012, and Perkins was added in 2013. Perkins is a deep sandy loam soil, low in soil organic matter and prone to leaching of mobile nutrients like S and N (Teller fine sandy loam, 1–3% slope, fine-loamy, mixed, active, thermic Udic Argiustolls). The Lahoma location is a Grant silt loam (1–3% slope, fine-silty, mixed, superactive, thermic Udic Argiustolls). At Lake Carl Blackwell in 2011–2012, trials were established on Port silt loam (fine-silty, mixed, superactive, thermic Cumulic Haplustolls), and in 2013–2014 on Port–Oscar (fine-silty, mixed, superactive, thermic Typic Natrustalfs) complex, both 0 to 1% slope.

In 2011 and 2012, a randomized complete block experimental design with four replications and 15 treatments was used (Table 1). Treatments included urea ammonium nitrate (UAN; 28–0–0) at 0, 40, and 80 kg N ha^{-1} applied preplant. Foliar application comprised of two sources, UAN (28–0–0) and N-Sure (28–0–0), applied at 10 and 20 kg N ha^{-1}, respectively. Sulfur was foliar-applied as gypsum

Table 1. Treatment structure in Oklahoma at Lahoma (LAH) 2011–2012 and 2012–2013, and Lake Carl Blackwell (LCB), 2011–2012.

Treatment	Preplant N rate†	Foliar N rate	Foliar N source	Foliar S rate‡
	———kg ha^{-1}———			kg ha^{-1}
1	–	–	–	–
2	40	–	–	
3	40	10	UAN	–
4	40	10	UAN	6
5	40	10	N-SURE	–
6	40	20	UAN	–
7	40	20	UAN	6
8	40	20	N-SURE	–
9	80	–	–	–
10	80	10	UAN	–
11	80	10	UAN	6
12	80	10	N-SURE	–
13	80	20	UAN	–
14	80	20	UAN	6
15	80	20	N-SURE	–

† Preplant N source was UAN (28–0–0).

‡ Foliar S source was gypsum.

at 6 kg S ha^{-1}. When diluting gypsum, it was left in water for 24 h to allow sufficient time to dissolve.

In the fall of 2013, trials were conducted at three locations, Perkins, Lahoma, and Lake Carl Blackwell, OK. For the year 2013, trials were restructured in a randomized complete block with three replications and seven treatments (Table 2). Urea ammonium nitrate (28–0–0) was applied preplant at 0 and 40 kg N ha^{-1}, and 20 kg N ha^{-1} was foliar-applied. Preplant N was surface-applied using an all-terrain vehicle (ATV) with a 3-m boom using streamer nozzles. Gypsum was applied preplant at 0, 3, and 6 kg S ha^{-1} and liquid S (MAX-IN S) was foliar-applied at rates of 3 and 6 kg S ha^{-1}. Preplant gypsum was broadcast-applied and then incorporated. All the foliar material was dissolved in water to make a 1-L solution, applied at the flag leaf stage, and delivered with a CO_2 backpack sprayer. The use of Tee Jet flat fan nozzles and an application pressure of 275.8 kPa yielded fine spray droplets.

During 2011 and 2012, composite soil samples from the surface (0–15 cm) were collected. Composite soil samples included 15 to 20 soil cores from the entire area. For the year 2013, soil samples were taken before planting and after wheat harvest. Before planting, by plot soil samples were collected from the surface (0–15 cm). Post-harvest soil samples were taken by plot at 0- to 15- and 15- to 45-cm depths. All samples were oven-dried at 65°C and ground to pass through a 2-mm sieve. Soil samples were analyzed for pH, NO_3–N, NH_4–N, SO_4–S, P, and K. Soil pH was measured using a calomel electrode in 1:1 (soil/water) ratio. Nitrate N and ammonium N were measured using 5 g of soil and 15 mL of 1.0 M KCl and shaken for 30 min. Extracts were run through a Lachat Quickchem 8000 automated flow-injection analyzer. Analysis for SO_4–S was accomplished by extracting the associated solution from 10 g soil and 25 mL of 0.008 M calcium monophosphate, shaken for 30 min, and analyzed using an inductively coupled plasma spectrometer. Additionally, P and K were extracted using Mehlich 3 solution and quantified by a Spectro ICP spectrometer.

A vacuum planter was used for planting at a seeding rate of 100 kg ha^{-1}. Detailed field activities information for each site year is noted in Table 3. At maturity, wheat was harvested using a Massey Ferguson 8XP self-propelled combine. Grain subsamples were collected from each plot and moisture was adjusted to 12.5%. Grain samples were oven-dried at 75°C for 2 d and then ground using a Thomas Wiley Laboratory mill (Thomas Scientific, Swedesboro, NJ, USA) and rolled to pass a 100-µm sieve. Total grain N analysis was determined using a LECO Truspec CN dry combustion analyzer (Leco Corp., St Joseph, MI, USA) (Schepers et al., 1989).

Data were analyzed separately for each year and location. Data were analyzed using Statistical Analysis System, PC SAS v. 9.4 (SAS Institute, 2004). Analysis of variance was used to determine significant effects of treatments on grain yield and grain N content. Treatment differences among specific treatment groupings were identified using non-orthogonal-single-degree-of-freedom contrasts and mean separation.

RESULTS AND DISCUSSION

Soil test results for the three experimental sites showed sufficient levels of S at all three locations. On average sulfate-S was 29, 19, and 33 kg S ha^{-1} in 2011, 2012, and 2013, respectively, at Lahoma (Table 4). For LCB, this was 126 kg S ha^{-1} in 2011 and 24 kg S ha^{-1} in 2013. In Perkins, it was 35 kg S ha^{-1} in 2013. Furthermore, Soil nitrate N levels ranged between 4 and 33 kg N ha^{-1} across all site years (Table 4). Soil pH at all locations ranged from 5 to 7.7 (Table 4). Soil organic C ranged from 6.4 to 8.5 g kg^{-1} across all locations (Table 4). Also, initial soil test values showed adequate nutrient levels for all years and locations (Table 4). The post-harvest surface (0–15 cm) soil samples taken in 2013–2014 showed a decreased level of sulfate-S in comparison to preplant soil samples (Table 4).

Analysis of variance showed that there were significant treatment differences in Lahoma 2011–2012 and 2012–2013 (Table 5). Lahoma grain yields ranged from 1752 to 2907 kg ha^{-1} in 2011–2012, 692 to 1501 kg ha^{-1} in 2012–2013, and 1709 to 2389 kg ha^{-1} in 2013–2014 (Tables 5 and 6). Lower grain yields at Lahoma in 2012–2013 were due to a dry fall, poor plant stands, and higher rainfall from late March to harvest (Fig. 1). Also, late spring freezes in February and March (Table 7) possibly induced extreme stress and poor root system development, which further impaired grain yield. In general, wheat performs well in an optimum temperature range of 17 to 23°C throughout an entire growing season, with a minimum

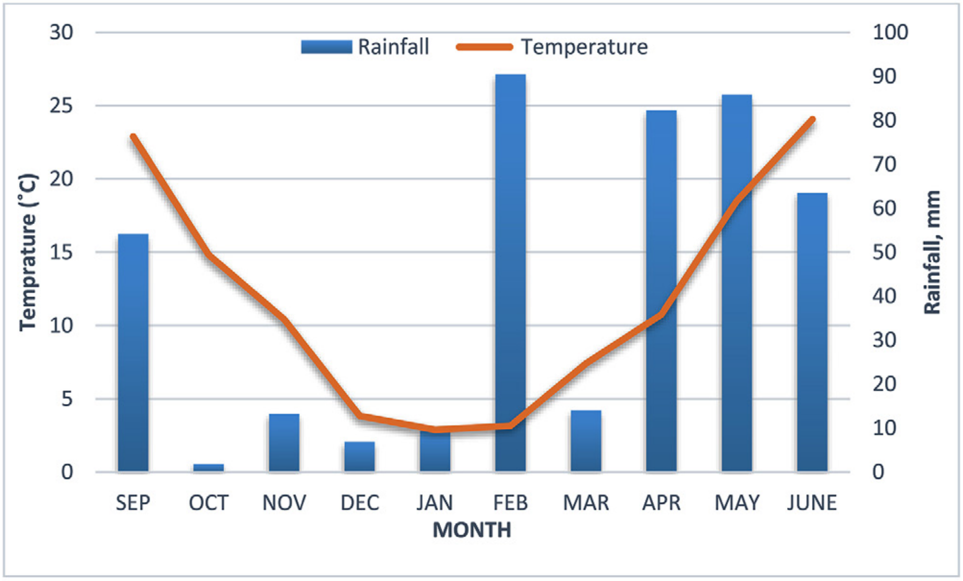

Fig. 1. Average monthly air temperature and total monthly rainfall during the 2012–2013 winter wheat growing season at Lahoma, OK (source: www.mesonet.org).

Table 2. Treatment structure in Oklahoma at Lahoma (LAH), and Lake Carl Blackwell (LCB) and Perkins (PERK), for 2013–2014.

Treatment	Preplant N rate†	Foliar N rate‡	Preplant S	Preplant S source	Foliar S rate	Foliar S source
	kg ha^{-1}				kg ha^{-1}	
1	–	–	–	–	–	–
2	40	–	–	–	–	–
3	40	–	–	–	6	Max in S
4	40	–	6	Gypsum	–	–
5	40	20	6	Gypsum	–	–
6	40	20	–	–	6	Max in S
7	40	20	3	Gypsum	3	Max in S

† Preplant N source was UAN (28–0–0).

‡ Foliar N source was UAN (28–0–0).

Table 3. Field activities for each location, 2011–2013.

	2011–2012		2012–2013	2013–2014		
Field activity	Lake Carl Blackwell	Lahoma	Lahoma	Lake Carl Blackwell	Lahoma	Perkins
Preplant N fertilization	28 Sept.	27 Sept.	4 Oct.	10 Oct.	9 Oct.	8 Oct.
Seeding rate, kg ha^{-1}	100	100	100	100	100	100
Planting	14 Oct.	14 Oct.	11 Oct.	24 Oct.	24 Oct.	23 Oct.
Top-dress	7 Mar.	13 Mar.	13 May	19 Mar.	20 Mar.	20 Mar.
Harvest	4 June	25 May	21 June	30 June	17 June	16 June

Table 4. Soil chemical properties determined from preplant soil samples (0–15 cm) in Oklahoma at Lahoma (LAH), for 2011, 2012, and 2013; Lake Carl Blackwell (LCB) for 2011 and 2013; and Perkins (PERK) for 2013. Post-harvest (0–15 and 15–45 cm) at Lahoma (LAH), Lake Carl Blackwell (LCB), and Perkins (PERK) for 2013.

			Preplant					Post-harvest	
Location	pH†	Organic C	NO$_3$–N‡	NH$_4$–N‡	K§	P§	SO$_4$–S¶	SO$_4$–S¶ (0–15 cm)	SO$_4$–S¶ (15–45 cm)
		g kg^{-1}	mg kg^{-1}						
LAH 2011	5.7	6.9	7	11	208	12	13		
LAH 2012	5.7	7.9	4	5	300	14	8		
LAH 2013	6	8.0	2	13	270	26	15	3	3
LCB 2011	7.7	7.8	5	5	129	14	56		
LCB 2013	5.6	8.5	15	24	121	36	11	2	1
PERK 2013	5	6.4	3	14	136	62	16	2	1

† 1:1 soil/water ratio.

‡ 2 M KCl extracting solution.

§ Mehlich III.

¶ Inductively coupled argon plasma spectrophotometer (ICP).

Table 5. Average grain yield (GY) and grain nitrogen (GN) by treatment in Oklahoma at Lahoma (LAH) in 2011–2012 and 2012–2013, and Lake Carl Blackwell (LCB) in 2011–2012.

	LAH 2011–2012		LCB 2011–2012		LAH 2012–2013	
Treatments	GY	GN	GY	GN	GY	GN
	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}
1	1752	1.7	2025	1.4	692	1.9
2	1851	1.8	2603	1.5	1085	2.0
3	2100	1.8	2812	1.6	1147	2.1
4	2190	1.7	2411	1.7	1027	2.0
5	2073	1.8	2708	1.7	1144	2.0
6	1926	1.8	2851	1.7	1005	2.1
7	2072	1.8	2738	1.8	1070	2.2
8	2489	1.8	2520	1.7	1262	2.1
9	2604	1.9	2758	1.8	1364	2.1
10	2641	1.9	2343	1.6	1445	2.1
11	2907	1.9	2588	1.7	1501	2.2
12	2638	1.8	2236	1.7	1416	2.2
13	2292	1.9	3202	1.7	1027	2.3
14	2391	1.9	2497	1.9	1359	2.3
15	2701	2.0	2411	1.7	1203	2.2
Pr > F	0.0268	0.0424	0.8484	0.4512	0.0079	0.0001
SED†	332	0.08	432	0.15	182	0.06
CV‡, %	18	5	21	11	19	4

† SED, standard error of the difference between two equally replicated means.

‡ CV, coefficient of variation.

Table 6. Average grain yield (GY) and grain nitrogen (GN) for the treatment levels in Oklahoma at Lahoma (LAH), Lake Carl Blackwell (LCB), and Perkins (PERK) in 2013–2014.

Treatments	LAH		LCB		PERK	
	GY	GN	GY	GN	GY	GN
	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mg kg^{-1}
1	1810	2.4	746	2.1	708	2.1
2	1709	2.1	1008	2.1	1080	2.1
3	1936	2.5	923	2.3	1366	2.0
4	2016	2.0	1094	2.2	1322	2.0
5	2389	2.5	948	2.2	1316	2.6
6	1725	2.4	906	2.4	1254	2.1
7	1875	2.6	1103	2.3	1331	2.1
Pr > *F*	0.2845	0.1088	0.1954	0.1446	0.0643	0.2285
SED†	270	0.20	91	0.10	183	0.24
CV‡, %	17	10	12	6	19	14

† SED, standard error of the difference between two equally replicated means.

‡ CV, coefficient of variation.

Table 7. Freezing days in February and March with temperature lower or near to 0°C for wheat growing season, 2012–2013, Lahoma, OK (source: www.mesonet).

Month	Day	°C
Feb.	21	−2.0
Feb.	22	−7.1
Feb.	23	−2.4
Feb.	25	0.8
Feb.	26	−0.9
Feb.	27	−1.8
Feb.	28	−1.1
Mar.	1	−1.6
Mar.	24	−0.5
Mar.	25	0.0

and maximum temperature of 0 and 37°C, respectively, and beyond where growth stops (Porter and Gawith, 1999). Nonetheless, wheat cultivars differ regarding temperature resistance over the growing season. Single-degree-of-freedom-contrasts for wheat grain yield (preplant N linear) were significant ($P > 0.05$) at Lahoma for 2011–2012 and 2012–2013, respectively (Table 8). These results agree with Reneau et al. (1986), who noted a linear yield increase with N application while comparing N × S interaction, and reported no effect on yield due to S application.

Analysis of variance showed that there were no significant treatment differences at Lake Carl Blackwell in any of the years (Tables 6 and 8). Average grain yields at LCB ranged from 2025 to 3202 kg ha^{-1} and 746 to 1103 kg ha^{-1} for 2011–2012 and 2013–2014, respectively (Tables 5 and 6). For 2011–2012, Lake Carl Blackwell had more tillers and better plant stands. Also at this site, adequate and timely rainfall was received from late March to mid-

Table 8. Single degree-of-freedom contrasts for grain yield (GY) and grain nitrogen (GN) in Oklahoma at Lahoma (LAH) in 2011–2012 and 2012–2013, and Lake Carl Blackwell (LCB) in 2011–2012.

Single df contrasts	LAH 2011–2012		LCB 2011–2012		LAH 2012–2013	
	GY	GN	GY	GN	GY	GN
	Pr > *F*					
Preplant linear	*	ns†	ns	*	**	**
Preplant quadratic	ns	ns	ns	ns	ns	ns
UAN vs. NSURE	ns	ns	ns	ns	ns	ns
Fol‡ 10 vs. 20	ns	ns	ns	ns	ns	**
(UAN vs. NSURE) (Pre 40 vs. 80)	ns	ns	ns	ns	ns	ns
(Pre§ 40 vs. 80) (Fol 10 vs. 20)	ns	ns	ns	ns	ns	ns
(UAN vs. NSURE) (Fol 10 vs. 20)	ns	ns	ns	ns	ns	ns
(UAN vs. NSURE) (Pre 40 vs. 80) (Fol 10 vs. 20)	ns	ns	ns	ns	ns	*
S vs. none	ns	ns	ns	ns	ns	ns
(S vs. none) (Pre 40 vs. 80)	ns	ns	ns	ns	ns	ns
(S vs. none) (Fol 10 vs. 20)	ns	ns	ns	ns	ns	ns
(Pre 40 vs. 80) (Fol 10 vs. 20)	ns	ns	ns	ns	ns	ns
(S vs. none) (Pre 40 vs. 80) (Fol 10 vs. 20)	ns	ns	ns	ns	ns	ns

* Significant at the 0.05 level.

** Significant at the 0.01 level.

† Not significant at the 0.1 level.

‡ Foliar application.

§ Preplant application.

Table 9. Single degree-of-freedom contrasts for grain yield (GY) and grain nitrogen (GN) in Oklahoma for Lahoma (LAH), Lake Carl Blackwell (LCB), and Perkins (PERK), 2013–2014.

	LAH		LCB		PERK	
Single df contrasts	GY	GN	GY	GN	GY	GN
	Pr > F					
Trt‡ vs. control	ns†	ns	**	ns	**	ns
N only vs. other	ns	ns	ns	ns	ns	ns
Pre§ N vs. Pre and Fol¶ N	ns	*	ns	ns	ns	ns
S vs. none	ns	ns	ns	ns	ns	ns
Fol S vs. Pre S	ns	ns	ns	ns	ns	ns
Split vs. singles	ns	ns	ns	ns	ns	ns

* Significant at the 0.05 level.

** Significant at the 0.1 level.

† Not significant at the 0.1 level.

‡ Treatment.

§ Preplant application.

¶ Foliar application.

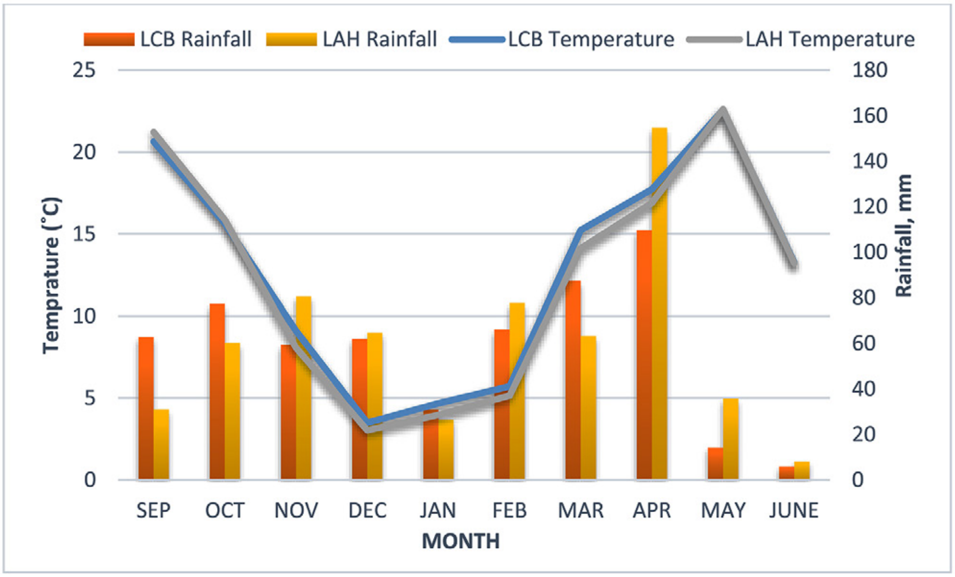

Fig. 2. Average monthly air temperatures and total monthly rainfall during the 2011–2012 winter wheat growing season at Lake Carl Blackwell (LCB) and Lahoma (LAH), OK (source: www.mesonet.org).

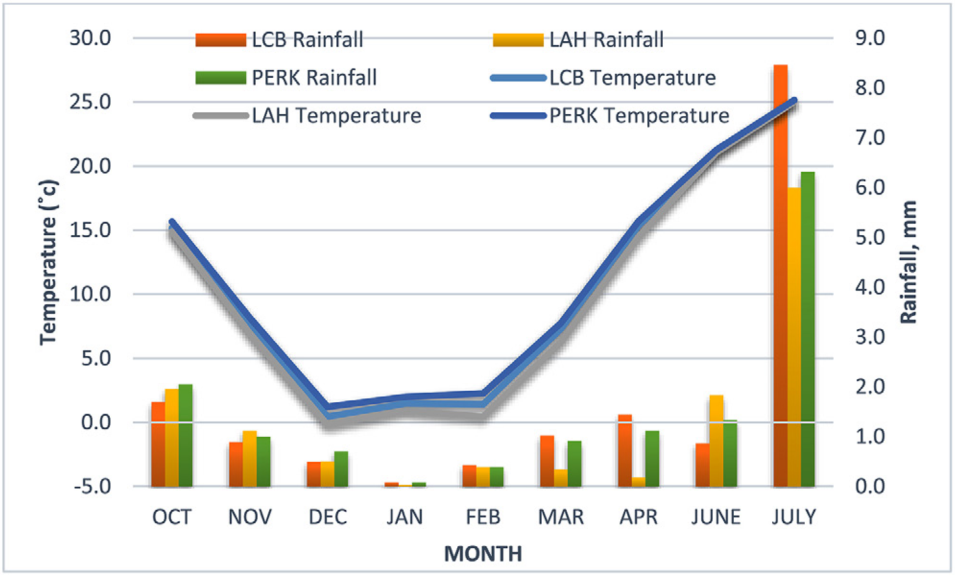

Fig. 3. Average monthly air temperature and total monthly rainfall during the 2013–2014 winter wheat growing season at Lake Carl Blackwell (LCB), Lahoma (LAH), and Perkins (PERK), OK (source: www.mesonet.org).

April (Fig. 2 and 3). Moisture demands from late March to mid-April can be critical for winter wheat in Oklahoma. In 2013, this location received higher rainfall in July. Due to wet/saturated fields, mechanical harvest was delayed by 15 d compared with the other locations. The lower yields for LCB in 2013–2014 was in part due to the continuous wet period during harvest leading to shattering losses and decreased grain weight (Table 6). It was noted with single-degree-of-freedom-contrasts that yields were significant (P > 0.01) when treatments were compared with check plot at Lake Carl Blackwell (2013–2014) (Table 9).

Similarly, no treatment differences were noted at Perkins with analysis of variance (Table 6). However, single-degree-of-freedom-contrasts showed higher yields when treatments were applied compared with check plot (Table 9). At the Perkins site, yields ranged between 708 and 1366 kg ha^{-1} for 2013–2014 (Table 6). Winter wheat performs best with a pH near 5.5. Yields were lower at Perkins, in part due to lower soil pH (pH = 5.0, Table 4) in comparison to the other locations (Anderson et al., 2013; Schroder et al., 2011). Low soil acidity likely increased the level of aluminum, which affects root growth.

Grain N at Lahoma ranged between 1.7 and 2.0, 1.9 and 2.3, and 2.0 and 2.6 mg kg^{-1} for the year 2011–2012, 2012–2013, and 2013–2014, respectively (Table 5 and 6). Analysis of variance showed a significant treatment effect on grain N at Lahoma in the year 2011–2012 and 2012–2013 (Table 5). Grain N at LCB ranged from 1.4 to 1.9 and 2.1 to 2.4 mg kg^{-1} for 2011–2012 and 2013–2014, respectively, whereas at Perkins, 2013–2014 was between 2.0 and 2.6 mg kg^{-1} (Table 6). For all locations, grain N was higher when grain yields were lower. Reduction in protein with yield decrease was due to the dilution effect, where a fixed amount of N taken up by the crop has to be spread across greater grain mass increasing yields and reducing protein content (Simmonds, 1995). Single-degree-of-freedom contrasts revealed that grain N (preplant N linear) was significant (P > 0.01) for Lake Carl Blackwell and Lahoma 2012–2013 (Table 8).

Comprehensive field results across site-years showed that applications of foliar S and N did not increase grain yield and grain N for winter wheat. Furthermore, the interaction between foliar S, foliar N, preplant S, and preplant N was not significant for grain yields and grain N across all site-years. Another wheat study by Salvagiotti et al. (2009) noted no interaction between S and N at the lower N rates; however, greater N uptake was observed with S at higher N rates. They interpreted that at low N rates soil S may have been enough to meet growing crop N demand. Furthermore, Salvagiotti and Miralles (2008) noted that S addition is valuable when N was not a limiting factor. Thus, it is crucial to consider residual S levels before applying additional S.

CONCLUSIONS

This work evaluated the effects of S and N, both preplant and foliar-applied on winter wheat grain yield and grain N content. Comprehensive field results showed that applications of foliar S did not increase grain yield and grain N for winter wheat over sites and years. Although Perkins was a deep sandy loam soil, low in soil organic matter, it also did not show a response to applied S. The lack of finding any S response is likely due to the adequate S supply from the soil as indicated by the preplant soil test, and/or greater subsoil S. Furthermore, the interaction between foliar S, foliar N, preplant S, and preplant N were not significant for grain yields and grain N. The application of S fertilizer is not likely to be beneficial in this region unless a low level of soil S is identified through soil testing. Therefore, preplant soil sample analysis is encouraged to further guide farmers on decisions of whether or not to apply S. Also, S responses to a certain extent were expected as soil organic C levels were all less than 8.5 g kg^{-1}. This becomes disconcerting, especially when commercial S applications are encouraged despite a lower likelihood of response.

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