CO-LIMITATION OF NITROGEN AND SULFUR IN HARD RED WINTER WHEAT

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ABSTRACT

Quantifying the interactions of nutrients in wheat production are essential to reduce the yield gap. Nitrogen and S deficiencies (individually or in combination) reduce wheat yields and increase the yield gap. Our objectives were to quantify the colimitation of N and S in wheat in Kansas. We established an experiment with three N rates (50, 100, and 150% of the N required for an yield goal of 60 bu/a), four S rates (0, 10, 20, and 40 lb S/a), and three genotypes (LCS Mint, SY Monument, and Zenda) in a split-split-plot design across eight Kansas environments distributed on three growing seasons. Grain yields ranged from 12 to 86 bu/a across treatment combinations and environments. Grain yield increased with increasing N rate at all locations (2 to 13 bu/a), while the addition of S increased grain yield at two locations (up to 40 bu/a). Increasing N rates decreased N use efficiency (NUE), and similar results occurred for S. However, S applied at 10 lb/a increased SUE in environments where soil-S content at sowing was limiting. The co-limitation analysis suggested that the optimal N:S ratio for grain was 17.3. Through a field study conducted in eight environments, we demonstrated that N and S interact in the determination of wheat yield and nutrient use efficiencies, and an optimum N:S ratio that decreases the yield limitation by either nutrient exists.

INTRODUCTION

At historical time scales, N has been the most limiting nutrient to crop yields; thus, N fertilizer management has been extensively researched (e.g., Jaenisch et al., 2019; Lollato et al., 2019; 2021). Nitrogen use efficiency (NUE) is the grain yield per unit of available N, and is determined by N uptake efficiency (i.e., the ratio between N uptake and N available) and N utilization efficiency (i.e., the ratio between yield and N uptake) (Moll et al., 1982). NUE is affected by agronomic management, of particular importance to the current study, the availability of other nutrients such as sulfur (S).

Positive agronomic responses in commercial crops to the addition of S fertilizer seem to be more apparent in recent years (Girma et al., 2005; Camberato and Casteel, 2010) due to the decline in organic matter in cultivated soils (Lollato et al., 2012) and the decrease in S dioxide deposition in the rainfall (Ceccotti, 1996). Sulfur is also an essential element to crops, playing variety of roles within the plant (Duke et al., 1986) thus S deficiency can reduce yield (Salvagiotti and Miralles, 2008).

In wheat, S seems to interact with N to determine NUE by impacting soil N recovery rather than increasing N utilization efficiency (Salvagiotti et al., 2009). Sulfur allowed for the production of more shoot biomass which increased root biomass and for greater soil exploration and uptake of N (Salvagiotti et al., 2009). Despite these previous efforts to untangle N and S impacts on wheat performance, to our knowledge, there have been no attempts to understand this interaction from a co-limitation perspective (Sterner and Elser, 2002). Because N and S seem to limit wheat yield in commercial Kansas wheat fields (Jaenisch et al., 2021), our objective was to determine N and S limitation effects on the nutrient use efficiencies and yield on wheat.

MATERIALS AND METHODS

Experimental locations and agronomic management

Field experiments were established in eight Kansas environments (E) resulting from the combination of locations and years. These were Ashland Bottoms during the 2018-19 and 2019-20 winter wheat growing seasons (Belvue silt loam soil); Belleville during the 2017-18 and 2019-20 winter wheat growing seasons (Crete silt loam soil); Manhattan during the 2017-18 season (Kahola silt loam soil); Hutchinson during the 2018-19 and 2019-20 seasons (Funmar-Taver loam soil); and Viola during the 2019-20 season (Milan loam soil). All experiments were conducted under rainfed conditions.

Winter wheat was sown using no-tillage practices following a previous soybean crop at all environments. Plots were seven 7.5-inch spaced rows by 30 ft long. Foliar fungicide was applied at anthesis at all locations so that disease incidence was not a confounding factor. Wheat was harvested using a small-plot Massey Ferguson 8XP combine and grain yield was corrected for 13.5% moisture.

Treatment structure and experimental design

The experiment was arranged in a 3 × 3 × 4 split-split-plot design with four replications. Three wheat genotypes (G) were assigned to whole plots, three N rates were assigned to sub-plots, and four S rates were assigned to sub-sub plots. The three genotypes were SY Monument, LCS Mint, and Zenda. Nitrogen was applied as urea ammonium nitrate (28N-0-0) and rates consisted of 50%, 100%, and 150% of KSU recommendations for a 60 bu/a yield goal. The actual amount of N applied depended on the initial soil NO_3-N in the 0-60 cm profile and ranged from 43 to 73 lb N/ac in the 50% yield goal, and from 110 to 198 lb N/ac in the 150% yield goal. Sulfur was applied as ammonium thiosulfate (12-0-0-26S) at 0, 10, 20, or 40 lb S/a. A pressurized CO_2 backpack sprayer was used to apply treatments at spring greenup.

Calculations and statistical analyses

The N and S use efficiencies were calculated using the definitions provided by Gastal et al. (2015), which takes into account the soil nutrient available at sowing plus the nutrient from applied fertilizer. A limitation in this nutrient use efficiency calculation is that it does not account for the contribution of N and S from the mineralization of soil organic matter during the growing season, potentially overestimating nutrient use efficiency. The N:S ratio were calculated in the wheat grain.

Analysis of variance was performed using “lmerTest” in R software version 3.4.0. Genotype, N rate, S rate, environment, and their interactions were considered fixed effects, while block nested within environment, and genotype nested within block, N rate nested within genotype, S rate nested within N rate were random effects (the latter accounted for the split-split-plot design). For the N:S stoichiometry, a linear-linear model was built using the “segmented” package to determine when either N or S were limiting in the wheat grain.

RESULTS

Across all environments, genotypes, and N and S rates, grain yield ranged from 12 to 86 bu/a with significant three-way interactions for E × N × S, E × G × N, and E × G × S. Increased N increased yields in all environments from 1.5 to 14 bu/a (Figure 1). This benefit of N rate to yield depended on S rate in three environments (AB19, AB20, Sum20) where the presence of S increased grain yield in as much as 40 bu/a. The E × G × N interaction was due to the genotype Zenda yielding the least in six environments at the lowest N rate, and yielding the highest as N rate increased in three environments.

Nitrogen use efficiency varied across environments and treatments (Figure 2). Interactions occurred for NUE among E × N × S and among E × G × S. The average NUE for each N rate across all S rates and environments was 25, 21, 17 lb/lb for the 50, 100, 150% N rate, respectively. Increasing N rate decreased NUE at all environments. In six locations, NUE decreased from 24 to 17 lb/lb as N rate increased from 50% to 150%. In two locations (AB19 and AB20), the zero S rate had significantly lower NUE as compared to treatments receiving a S application. In three environments (Bel18, Bel20, and Sum20), Monument and Mint resulted in a higher NUE than Zenda. Similarly to NUE, three-way interactions among E × N rate × S rate and E × G × S rate occurred for SUE (Figure 3). Across environments, the zero S rate resulted in the greatest SUE which ranged from 73-228 lb/lb, while the 40 lb S/a resulted in the lowest SUE (range: 36-82 lb/lb). The only exception was ASB19, where the addition of 10 lb S/a increased SUE as compared to the zero S rate by 18 and 24 lb/lb for the 100 and 150% N rates. In five environments, the addition of N increased SUE anywhere within the same S rate.

For N and S limited conditions, wheat yield increased with N:S until reaching the 95% maximum value at 17.3 (CI: 17.1-17.5) for the grain, decreasing afterwards (*p<0.001;* R^2=0.65).

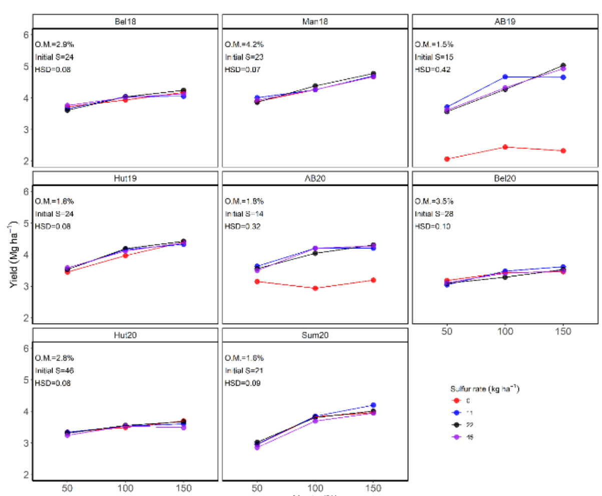

Figure 1. Average winter wheat gain yield affected by N rate (50, 100, and 150%), S rate (0, 10, 20, and 40 lb S/a), and environments (Bel18, Man18, AB19, Hut19, AB20, Bel20, Hut19, and Sum20). The Honest Significant Difference was calculated within

each environment. Soil samples were taken before sowing to determine organic matter (%) and initial plant available S at sowing (kg ha^{-1}).

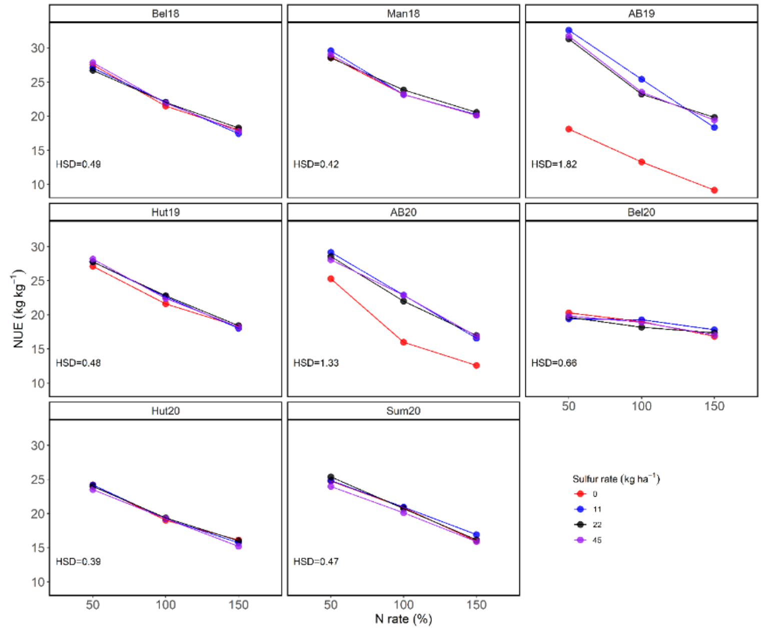

Figure 2. Mean nitrogen use efficiency (NUE) as affected by N rate (50, 100, and 150%), S rate (0, 10, 20, and 40 lb S/a), and environment (Bel18, Man18, AB19, Hut19, AB20, Bel20, Hut20, and Sum20). The Honest Significant Difference was calculated within each environment.

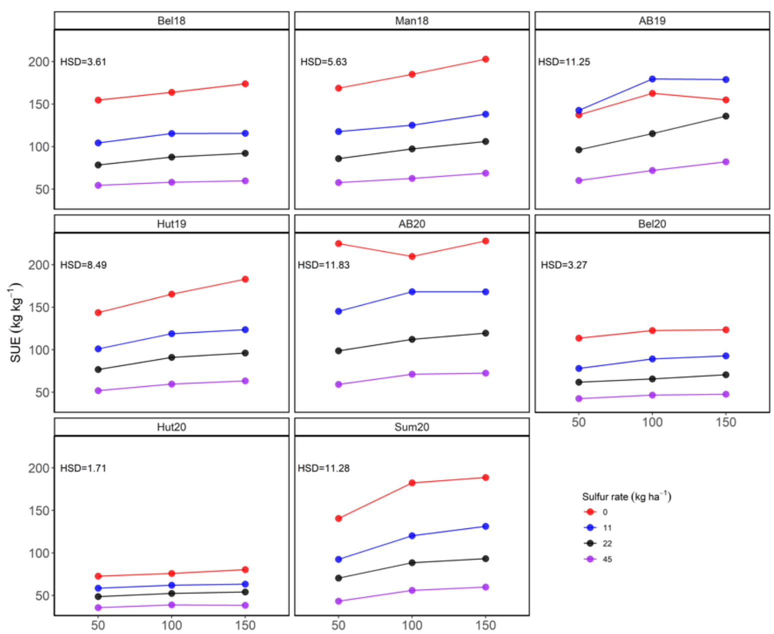

Figure 3. Mean sulfur use efficiency (SUE) as affected by N rate (50, 100, and 150%), S rate (0, 10, 20, and 40 lb S/a), and environment (Bel18, Man18, AB19, Hut19, AB20, Bel20, Hut20, and Sum20). The Honest Significant Difference was calculated within each environment.

Discussion

The range in wheat yield under the experimental conditions evaluated was similar to that reported in this region (Cruppe et al., 2021; Jaenisch et al., 2019; Perin et al., 2020). Wheat grain yield increased linearly with increases in N rate at all locations; however, the presence of S was only significant in two locations. The soil in these two environments were inherently low in plant available S at sowing (<20 kg S ha^{-1}) and had low organic matter (<1.8%) and applications of 10-20 lb S/a maximized yields. Similarly, Ramig et al. (1975) suggested that plant available S at sowing was sufficient at 17 kg S ha^{-1}, and Girma et al. (2005) suggested that yield responses to S fertilizer application are more likely to occur on low organic matter (<2%), coarse textured soils. In the remaining environments with greater soil S available at sowing and/or organic matter content, yield response to S fertilization was not expected.

Increases in NUE and SUE either derive from improved fertilizer recovery or internal efficiency in utilizing the uptake N and S (Salvagiotti et al., 2009). Proposed mechanisms include 1) N and S fertilization increased root growth and the larger explored rooting area allowed for greater uptake of N and S (Salvagiotti et al., 2009), and 2) N and S fertilization increased crop growth consequently increasing the demand of nutrients. Our findings of a N:S ratio of 17.3 in the grain are similar to what has been reported in the literature (Randall et al., 1981; Byers et al., 1987). In S deficient soils, the N:S ratios can be as high as 20:1 or as low as 12:1 which is the minimum N requirement (Camberato and Casteel, 2010). Grain N:S ratio offer a great opportunity to check for nutrient deficiencies at the end of a season (Randall et al., 1981).

CONCLUSIONS

While N and S interacted in the determination of wheat yield, impacting wheat NUE and SUE; the impact of S application was only apparent in coarse textured soils with low organic matter content. This suggests the need for judiciously management of S in winter wheat systems of Kansas. The colimitation approach presented here suggested that wheat yields maximized when N:S ratio in the grain approached 17.3.

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