IMPROVING WINTER WHEAT GRAIN YIELD AND NITROGEN USE EFFICIENCY USING NITROGEN APPLICATION TIME AND RATE

By

LAWRENCE AULA

Bachelor of Science in Agriculture
Gulu University
Gulu, Uganda
2009

Master of Science in Plant and Soil Science
Oklahoma State University
Stillwater, Oklahoma
2014

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Dissertation Approved:

Dr. Raun R. William

Dissertation Adviser

Dr. Arnall D. Brian

Dr. Abit M. Sergio

Dr. Weckler R. Paul

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Abstract: Preplant nitrogen (N) application which involves placing nutrients in the soil prior to seeding has been an integral part of crop production systems for decades. Some producers are known to apply N at least 21 days before planting. This may increase N loss and lower grain yield. This study evaluated the effect of time and rate of N application on winter wheat (*Triticum aestivum* L.) grain yield and N use efficiency (NUE). An experiment with a factorial arrangement of treatments was set up in a randomized complete block design with three replications. Treatments included four N rates (0, 45, 90 and 135 kg ha^{-1}) with each applied 7 and 30 days before planting, and at Feekes 5 (FK_5). Wheat grain was harvested using a combine. Grain N was analyzed using LECO CN 628 and LECO CN 828 for 2019 and 2020 grain harvest respectively. The difference method, $\frac{\text{Grain N from (fertilized plots - unfertilized plots)}}{\text{N applied}}$, was used to compute NUE. Apart from Efaw (2019), the interaction between time and rate of N application did not influence yield ($P \geq 0.07$). Nitrogen rate significantly affected yield and increased with increasing N rates ($P \leq 0.01$). Time of N application inconsistently affected yield and had no influence in some years. Overall, applying N at FK_5 resulted in approximately 3.3% higher yield than 2.9 Mg ha^{-1} achieved with preplant timing. In Lahoma, single degree of freedom contrasts showed a substantial NUE difference between FK_5 and 30 days before planting N application time ($P = 0.03$). This preplant N timing had 8.4% lower NUE compared to 24.0% for in-season management. Time and rate of N application are critical management approaches vital for yield and NUE improvement.

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CHAPTER I

IMPROVING WINTER WHEAT GRAIN YIELD AND NITROGEN USE EFFICIENCY USING NITROGEN APPLICATION TIME AND RATE

Abstract

Preplant nitrogen (N) application which involves placing nutrients in the soil prior to seeding has been an integral part of crop production systems for decades. Some producers are known to apply N at least 21 days before planting. This may increase N loss and lower grain yield. This study evaluated the effect of time and rate of N application on winter wheat (*Triticum aestivum* L.) grain yield and N use efficiency (NUE). An experiment with a factorial arrangement of treatments was set up in a randomized complete block design with three replications. Treatments included four N rates (0, 45, 90 and 135 kg ha^{-1}) with each applied 7 and 30 days before planting, and at Feekes 5 (FK_5). Wheat grain was harvested using a combine. Grain N was analyzed using LECO CN 628 and LECO CN 828 for 2019 and 2020 grain harvest respectively. The difference method, $\frac{\text{Grain N from (fertilized plots - unfertilized plots)}}{\text{N applied}}$, was used to compute NUE. Apart from Efaw (2019), the interaction between time and rate of N application did not influence yield ($P \geq 0.07$). Nitrogen rate significantly affected yield and increased with increasing N rates ($P \leq 0.01$). Time of N application inconsistently affected yield and had no influence in some years. Overall, applying N at FK_5 resulted in approximately 3.3% higher yield than 2.9 Mg ha^{-1} achieved with preplant timing. In Lahoma, single degree of freedom contrasts showed a substantial NUE difference between FK_5 and 30 days before planting N application time ($P = 0.03$). This preplant N timing had 8.4% lower NUE compared to 24.0% for in-season management. Time and rate of N application are critical management approaches vital for yield and NUE improvement.

1.1. Introduction

The use of fertilizers particularly nitrogen (N) in crop production has increased and will continue to rise as human population increases (Vitousek et al., 1997; Galloway et al., 2008) and projected to reach between 10.9 and 11.2 billion people by 2100 (Gerland et al., 2014; United Nations, 2015). Depending on the soil N status and environmental conditions in a given year, fertilizer N may increase crop yield and protein content (Thomason et al., 2000; Teal et al., 2007). This depends on the rate, source, method and time of N application for winter wheat (*Triticum aestivum* L.) which is well-documented in scientific journals (Sowers et al., 1994a; Raun and Johnson, 1999; Weisz et al., 2001; Melaj et al., 2003; Aula et al., 2020). In a study investigating the time of N fertilization, Boman et al. (1995) reported that time of N addition had little effect on wheat grain yield as well as soil residual ammonium N (NH_4-N). However, Melaj et al. (2003) showed that N application at tillering resulted in a high wheat grain yield in comparison to N applied at seeding. Although application of N in the fall or spring may not produce a substantial yield difference, the grain protein content of winter wheat in which N is applied in spring tends to be higher than that of fall (Fowler and Brydon, 1989; Boman et al., 1995; Brown and Petrie, 2006). This is possibly because N applied mid-season or late-season (just before or immediately after flowering) is assimilated by the crops to increase grain N and protein content (Woolfolk et al., 2002; Brown and Petrie, 2006).

Meanwhile, application of N especially at a high rate in the fall has been observed to result in lower nitrogen use efficiency (NUE) when compared to spring applied N (Sowers et al., 1994b). Nitrogen use efficiency may be further improved by the split application in fall and spring. Mahler et al. (1994) revealed the value of split application where they observed a better response to N when it was split-applied in the fall and spring with NUE reaching as high as 60% compared to a single fall (55%) or spring (53%) application.

A common time for N application among producers is preplant where all the N determined by laboratory soil testing is applied before planting. This N is usually applied at the same rate every year (Yadav et al., 1997) without recognizing the annual variability in yield potential and crop response to N (Raun et al., 2011). This is based on the traditional understanding that crop needs for N remain the same every year (Yadav et al., 1997). Split application of N where one portion is applied preplant and the other mid-season or at a later stage has also been reported in several research studies (Mahler et al., 1994; Sowers et al., 1994b; Randall and Sawyer, 2008). Preplant N application has not only been attributed by some scholars to a period when producers have adequate time to undertake farm operations but also because field conditions are best for N application (Randall and Sawyer, 2008). Most of the research studies that indicated the time for preplant N application either did so at planting (0 days) or within 15 days before sowing of wheat seeds (Wuest and Cassman, 1992; Melaj et al., 2003; López-Bellido et al., 2005; Barbieri et al., 2008). It is not uncommon to find work reporting preplant N timing as prior to or before planting (Brown and Petrie, 2006; Bushong et al., 2014). This may obscure our ability to pinpoint exactly when N was applied before planting and make an accurate interpretation of yield or any other variables evaluated with N applied preplant at different times. In some instances, producers apply N at least 21 days ahead of sowing seeds (Riley et al., 2001). This may explain why some producers use nitrification inhibitors to slow down the rate of conversion of ammonium (NH_4^+) to nitrate (NO_3^-) (Boswell et al., 1976; Slangen and Kerkhoff, 1984). Even though it is known that preplant N application may result in lower NUE and grain yield in comparison to mid-season sensor-based fertilization (Raun et al., 2002), the role of early preplant N on grain yield, and NUE of winter wheat has not been adequately addressed and documented. It may be possible that N applied preplant at different times may interact with quantity of N applied to produce different yield and NUE responses. By evaluating different preplant N timings against in-season timing at various N rates, decision about time and rate of N application could be improved for producers who use low-tech N management approaches (Arnall and Mullen, 2011).

This is particularly important considering that the 33% global NUE for cereal grains is low (Raun and Johnson, 1999).

This work, therefore, aims to evaluate winter wheat grain yield and NUE responses to N applied 30 and 7 days prior to planting, and at Feekes 5 growth stage (FK_5).

1.2. Literature Review

1.2.1. Grain yields as affected by time and rate of N application

Nitrogen is extensively used in crop production systems to attain high grain and/ or forage yield. The effect of time of N application on wheat grain yields has been investigated by numerous research scholars (Raun et al., 2002; Woolfolk et al., 2002; Brown and Petrie, 2006). In a conventional tillage system, Boman et al. (1995) observed no significant yield differences for N applied in fall or top dressed in spring. A similar result was found by López-Bellido et al. (2012) who observed no effect on yield for split applied N at sowing and stem elongation, and at tillering and stem elongation. A study conducted by Melaj et al. (2003) noted that N applied at tillering resulted in an increase in yield compared to N applied during planting. Barbieri et al. (2008) observed a similar result in six of the ten sites and a yield difference of 355 kg ha^{-1} was detected between N fertilization at sowing (5,110 kg ha^{-1}) and tillering (5,465 kg ha^{-1}). Brown and Petrie (2006) detected no yield difference between fall and spring applied N in winter wheat across three years of study. Averaged across the three years, they found spring applied N to yield (9.1 Mg ha^{-1}) slightly more than the fall-applied N (9.0 Mg ha^{-1}). They also found that splitting and applying 336 kg N ha^{-1} in fall and spring in the same experimental unit resulted, on average, in a 0.7 Mg ha^{-1} grain yield reduction when compared to 168 kg N ha^{-1} applied only in fall or spring. This illustrates that applying excessive amount of N may not lead to a grain yield improvement but instead increase the accumulation of residual nitrate in the soil (Cui et al., 2010). A study conducted by Bushong et al. (2014) reported that time of N application may not be important and can be applied preplant or topdressed in-season without affecting grain yield under rainfed conditions. However, López-Bellido et al. (2005) found a significant yield difference if total N is split applied equally as preplant and top-dressed at stem elongation compared to when total N was applied either as preplant or at stem elongation alone. They found the yield with total N split equally to be 6.5 Mg ha^{-1} while that applied preplant and/or at stem elongation were 5.8 and 6.1 Mg ha^{-1}, respectively. Raun et al. (2002) indicated that preplant N application had 253 kg ha^{-1} more grain yield than N applied midseason but that this difference was not significant. They reiterated the need to apply a portion of N preplant followed by midseason sensor-based N recommended rate in order to maximize grain yield. Early application of N prior to planting may subject N to volatilization loss (Sommer and Jensen, 1994) and leaching of nitrate (Mack et al., 2005) from the surface soil profiles before they are used by plants to develop vital plant products such as forage and grain. These coupled with denitrification and plant N loss, may lower the yield potential of a given growing environment. The often-contradictory results about the time of N application are a demonstration of the need for site-specific N management as recommendation for one site in a given year may not be applicable to the same site in another year or another site. This is where optical sensor technology becomes very important in determining crop N needs midseason without excessively applying N and compromising grain yield (Lukina et al., 2001; Raun et al., 2002).

1.2.2. Nitrogen use efficiency as affected by time and rate of N application

In recent decades, the focus of agricultural research has been tailored to improving nutrient use efficiencies (Raun and Johnson, 1999; Dhillon et al., 2017; Aula et al., 2019) particularly NUE for major cereal crops (Yang et al., 2017; Omara et al., 2019; Wallace et al., 2020). This is because a significant portion of N applied in the soil is not recovered in the grain leading to low NUE. The NUE for cereals at a global level is estimated at 33% (Raun and Johnson, 1999). Nitrogen use efficiency is known to be affected by the placement method, source, rate and time of

N application. Mahler et al. (1994) reported that split application of N between fall and spring resulted in a higher NUE ranging from 58 to 61% which was better than a single application either in fall (52 to 55%) or spring (51 to 53%). This suggests that split application increases the possibility of placing N at a time when it is needed by the crops. Remote sensing using proximal optical sensor has been known to improve NUE and the recommendation for fertilizer N mid-season by allowing adjustments to be made for changes in the soil N pool due to environmental factors (Raun et al., 2002; Thomason et al., 2002; Li et al., 2009). However, most producers apply a single rate of N prior to or during planting of wheat as recommended by soil test results (Randall and Sawyer, 2008). Furthermore, some producers apply the same rate of N every year (Yadav et al., 1997) while not considering the independence of crop response to applied N and grain yield (Raun et al., 2011). This may lower the efficiency at which N is absorbed and utilized by crops to form grains. Sowers et al. (1994b) revealed a difference in NUE for fall and spring applied N and reported that 68 and 80% of N in the plants were from soil N sources for spring and fall respectively. Conversely, Raun et al. (2002) observed no differences in NUE (22%) when 90 kg N ha^{-1} was either applied as a single dose at preplant or equally split applied as 45 kg N ha^{-1} at preplant and another 45 kg N ha^{-1} mid-season. Furthermore, they observed that 45 kg N ha^{-1} applied mid-season had a higher NUE of 25% than at 90 kg N ha^{-1} applied either as preplant (22%), mid-season (17%) or equally split applied (preplant and mid-season, 22%). This illustrates that higher NUE values are associated with lower N rates and may be particularly large if applied midseason. However, their study indicated that the highest NUE of 50% was obtained when one-half of the N rate determined by the mid-season optical sensor was applied. This result further reinforces the need to apply N at the time it is most needed by the plants.

1.2.3. Tillage systems effect on wheat grain yields and NUE

No-till which involves no soil disturbance of any kind has seen an enormous increase in acreage under crop production to as much as 111 million ha in 2009 (Derpsch et al., 2010; Claassen et al., 2018). This may be because of the potential benefits such as reduced runoff, soil erosion, production cost and increased soil organic matter among others (He et al., 2011; Williams and Wuest, 2011; Lal, 2013). As this practice increases among producers, agricultural scientists have investigated its role in improving crop yield and nutrient use efficiency while comparing it to conventional tillage which has remained an integral part of modern agriculture. López-Bellido et al. (2012) revealed a significant effect of the tillage system on wheat grain yield with no-till producing a 2.7% yield advantage over the 3.1 Mg ha^{-1} yield realized with conventional tillage. This was similar to results attained in a study conducted by Santín-Montanyá et al. (2017) who observed a significantly higher wheat grain yield of 3.6 Mg ha^{-1} under no-till management compared to 3.0 Mg ha^{-1} registered in a conventional tillage system. In a study investigating the effect of N rate and various tillage practices on yield, Habbib et al. (2017) noticed no significant difference in yield for the different tillage practices at a given N rate in 2014. However, they observed a marked dramatic increase in yield as the rate of N fertilization was increased. In 2015, they observed a substantial difference in wheat grain yields among the tillage practices in plots that received N where yields tended to be higher under no-till systems. Teal et al. (2007) observed mixed results from tillage systems on hard red winter wheat grain yield. At one of the experimental sites (Efaw), they did not detect a significant yield difference resulting from no-till and conventional tillage systems in 2001 and 2004. While in 2002 and 2003, yields were dramatically affected by tillage system with higher yields reported under conventional tillage. They further reported that a similar result (excluding 2003) was obtained at Lahoma but with higher yields recorded under no-till. When evaluating the effect of tillage on NUE, Teal et al. (2007) reported that when NUE was averaged across all N rates and years, no-till resulted in a higher NUE of 26% compared to 17% under conventional tillage with rolling coulter applicator (DMI) used to apply N. In the same study, they observed that when Noble or undercutting blade (V-blade) was used as the applicator, NUE for no-till (21%) was lower than for conventional tillage (25%). Noor (2017) in his review relevant to optimization of NUE in maize, noted that adoption of no-till or conservation tillage alongside correct use of other important agronomic practices may increase NUE. Habbib et al. (2017) also made a similar observation that N apparent recovery fraction under no-till might be improved to a greater extent by including cover crops in the cropping cycle. Rao and Dao (1996) reported an increase in grain N in no-till when N was placed 8 to 10 cm beneath the soil surface in comparison to broadcasting N on the soil surface. Similarly, they reported a yield increase when N was placed below the soil surface versus surface broadcasting. In the same study, they did not detect any difference in grain yield and grain N due to N placement when conventional tillage was used.

1.3. Materials and Methods

1.3.1. Experimental site and design

Two experiments were established, one at Efaw, Stillwater, OK and the second one at Lahoma, OK in 2018 and 2019. The soil at Efaw is a Kirkland Silt Loam (fine, mixed, thermic Udertic Paleustolls) while at Lahoma is a Grant Silt Loam (fine-silty, mixed, superactive, thermic, Udic Argiustoll). No-till and conventional tillage systems were used at Efaw and Lahoma, respectively. The experimental design was a randomized complete block design with twelve treatments and three replications. A factorial arrangement of treatments that included 4 N rates (0, 45, 90 and 135 kg ha^{-1}) and 3 N application times (7 and 30 days before planting, and at Feekes 5 growth stage [FK_5]) was used in this study. Each experimental unit within the blocks measured 3 m × 6 m and the blocks were separated from each other by an alley of 3 m. The treatment structure is shown in Table 1.1.

1.3.2. Experimental management and data analysis

Prior to preplant N application in each year, soil samples were collected at 0-15 cm soil depth and analyzed for NO_3^-, NH_4^+, P, K and soil pH (Table 1.2 and Table 1.3). Soil pH was analyzed using soil water ratio of 1:1. Nitrate and NH_4^+ were analyzed using 1M KCl and Lachat 8500 Series 2

Flow Injection Analyzer. Mehlich-3 was used to extract P and K followed by quantification using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Urea (46-0-0) was applied (broadcast) using a tractor-pulled fertilizer spreader to the soil surface 7 and 30 days prior to the sowing of seeds. At FK_5, N was broadcast applied by hand to the soil surface. The N applied in conventional tillage at Lahoma experimental site was incorporated immediately after application. However, urea N applied at FK_5 was not incorporated to avoid interfering with the root growth for wheat plants. The dates for planting of wheat and application of N are presented in Table 1.4. Winter wheat grain was harvested using a combine and yield recorded from the onboard computer yield monitor (Teal et al., 2007). Grain weight was adjusted to 12.5% moisture content. Wheat grain samples were dried in a forced-air oven at 66ºC for 48 hours and ground using Wiley mill (Arthur H. Thomas Co., Philadelphia, U.S.A) to pass through a 140-mesh sieve (100 µm). Subsamples of ground samples were placed in glass bottles equipped with four stainless steel metallic rods and assembled in polyvinyl chloride pipes that were then placed on an automatic roller for 24 hours to produce finer flour. A total of 150 mg of the finely ground flour for each treatment was analyzed for grain N concentration (%) using an automated LECO CN 628 and LECO CN 828 dry combustion analyzer (LECO Corporation, St. Joseph, MI, U.S.A) for 2019 and 2020 grain harvest respectively. Grain N concentration was then multiplied by grain yield to obtain grain N (kg ha^{-1}). Nitrogen use efficiency was computed using the difference method as defined in the equation below;

$$\text{NUE (\%)} = \frac{\text{Grain N from (fertilized plots - unfertilized plots)}}{\text{N applied}} \times 100$$

The data obtained were analyzed using R statistical package (R Core Team, 2019). Analysis of variance was used to evaluate the effect of time and rate of N application on grain yield, and NUE. Data visualization was achieved using ggplot2 within the tidyverse package (Wickham, 2016; Wickham et al., 2019).

Tables were generated using Flextable (Gohel, 2019a) and Officer (Gohel, 2019b) packages. Using the Agricolae package, treatment means were generated and separated by LSD at the 0.05 probability level (de Mendiburu, 2016). The p-values were adjusted using Bonferroni. Single degree of freedom contrasts were also performed using gmodels package (Warnes et al., 2018) to evaluate for the differences among specific treatment levels.

1.4. Results

1.4.1. Grain Yield, Lahoma

In 2019, the interaction between time and rate of N application did not influence winter wheat grain yield (P = 0.55) (Table 1.5). The main effects of rate and time of N application had a significant impact on winter wheat grain yield (P < 0.01) (Table 1.5). Grain yield increased as the rate of N application was increased from 0 to 135 kg ha^{-1} (Figure 1.1). Yield in the unfertilized check plot was 1.8 Mg ha^{-1}. This was statistically different from the grain yield obtained with the application of 45 and 90 kg ha^{-1}. Yield at 45 and 90 kg ha^{-1} exceeded that of the check plot by 31.5 and 44.5% respectively (Figure 1.1). Single degree of freedom contrasts showed no significant difference between grain yield realized by applying 45 and 90 kg N ha^{-1} (P = 0.23) (Table 1.6). Yield obtained with 135 kg N ha^{-1} was much higher than the 2.4 Mg ha^{-1} grain yield obtained at 45 kg N ha^{-1} by 27.0% (Figure 1.1). This was also validated by a single degree of freedom contrast analysis indicating that the yield difference between 45 and 135 kg N ha^{-1} was large (P < 0.01) (Table 1.6). Yield for N applied at 90 kg ha^{-1} was 2.6 Mg ha^{-1} and this was significantly lower than yield achieved with 135 kg N ha^{-1} by 15.5% (P = 0.04) (Table 1.6).

During the same year, time of N application also affected winter wheat grain yield (P < 0.01) (Table 1.5). Applying N 30 and 7 days before planting resulted in similar grain yields. Yield for N applied 30 and 7 days prior to planting was markedly different from that attained with N applied at FK_5 ($P = 0.01$; Table 1.6). On average, N application prior to planting led to 2.7 Mg ha^{-1} grain yield that was 29.2% larger than fertilization at FK_5 (Figure 1.2).

Similarly, time and rate of N application did not interact to significantly influence grain yield in 2020 ($P = 0.07$) (Table 1.5). As main effects, only rate of N application had a substantial effect on winter wheat grain yield ($P < 0.01$; Table 1.5). Grain yield was similar for N applied at the rate that range from 0 to 90 kg ha^{-1}. However, single degree of freedom contrast revealed that 135 kg N ha^{-1} led to a 63.8% significantly higher grain yield than 2.0 Mg ha^{-1} achieved with 45 kg ha^{-1} (Figure 1.1; Table 1.6).

Still in 2020, time in which N was applied did not affect wheat grain yield ($P = 0.42$; Table 1.5). Contrasting N applied 30 days before planting to N applied 7 days prior to planting or to N applied at FK_5 did not show any grain yield differences ($P \geq 0.31$; Table 1.6). A similar result was observed for the contrast between N applied 7 days before planting and at FK_5 ($P = 0.70$; Table 1.6). Although time of N application did not affect winter wheat grain yield in 2020, applying N at FK_5 led to a 18.3% higher grain yield when compared to 2.4 Mg ha^{-1} yield for N applied 30 days prior to planting (Figure 1.2). Nitrogen application 7 days prior to planting also had a slight yield advantage of 11.4% over N applied 30 days before planting (Figure 1.2).

1.4.2. Grain Yield, Efaw

Grain yield adjusted to 12.5% moisture content is presented in Figure 1.1. In 2019, grain yield at Efaw was significantly affected by the interaction between rate and time of N application ($P = 0.03$; Table 1.5). This suggests that the effect of time of N application on winter wheat grain yield depended on the rate of N applied. Alternatively, the effect of N rate on winter wheat grain yield was also a function of time of N application. The interaction plot in Figure 1.3 showed that increasing N rate and applying it either 7 days before planting or at FK_5 resulted in the largest grain yield. Furthermore, application of N earlier than the planting date seems to favor grain yield only when N rates are low (Figure 1.3). The largest grain yield (4.2 Mg ha^{-1}) was obtained with 135 kg N ha^{-1} applied at FK_5 and exceeded yield for 135 kg N ha^{-1} applied 7 and 30 days prior to planting by 9.7 and 20.4% (non-significant) respectively (Table 1.7). This yield difference increased to approximately 83.6% without application of N to winter wheat crops. Application of 135 kg N ha^{-1} at FK_5 started to have a significantly larger grain yield when compared with the grain yield obtained with 90 kg N ha^{-1} applied 30 days before planting. This timing and rate of N application created a 20.7% grain yield difference.

In 2020, rate and time of N application did not interact to substantially affect wheat grain yield ($P = 0.16$) (Table 1.5). Evaluation of main effects showed a significant effect of rate of N application on winter wheat grain yield ($P < 0.01$) (Table 1.5). Grain yield in the unfertilized check plot was substantially lower than yields achieved at other N rates that ranged from 90 to 135 kg N ha^{-1} (Figure 1.1). These rates contributed to at least a 15.2% significantly larger grain yield than 3.1 Mg ha^{-1} resulting from wheat production without N fertilization (Figure 1.1). A grain yield of 3.9 Mg ha^{-1} for 135 kg N ha^{-1} was about 12.3% higher than but similar to yield obtained by applying 45 kg N ha^{-1} ($P = 0.08$; Table 1.6). Application of additional 45 kg N ha^{-1} to 90 kg N ha^{-1} provided no added yield benefit ($P = 0.18$; Table 1.6). Nevertheless, 135 kg N ha^{-1} had 8.9% more grain yield than 2.9 Mg ha^{-1} grain yield realized with 90 kg N ha^{-1} (Figure 1.1).

Like N rate, time of N application in 2020 had a significant effect on winter wheat grain yield ($P < 0.01$) (Table 1.5). Delaying and applying the entire amount of N until FK_5 led to a significantly higher grain yield of 3.9 Mg ha^{-1} when compared to N applied 7 and 30 days before planting ($P \leq 0.01$; Table 1.6). On average, grain yield for N applied at FK_5 exceeded that of N applied 7 and 30 days before planting by 17.1% (Figure 1.2). While grain yield for N applied 7 days before planting was larger than for N applied 30 days before planting by 2.0% (Figure 1.2), the difference was not significant ($P = 0.72$; Table 1.6).

1.4.3. Nitrogen Use Efficiency, Lahoma

Nitrogen use efficiency measured as nitrogen in the fertilized plot less nitrogen in unfertilized check plot divided by N applied is presented on the right-hand panel of Figure 1.4. The interaction between time and rate of N application had little effect on NUE in 2019 ($P = 0.69$; Table 1.5). Because of this, the study evaluated the influence of each main effect on winter wheat NUE. Application of N at different rates resulted in similar NUE values for grain winter wheat ($P = 0.39$; Table 1.5). Nitrogen use efficiency averaged 19.5% across all the N rates. Overall, NUE was low at this site with the highest NUE of 22.0% measured at 45 kg N ha^{-1} (Figure 1.4). Increasing N rate from 45 to 135 kg ha^{-1} showed a reduction of NUE to 19.1%, indicating that N rate and NUE are negatively related. Furthermore, single degree of freedom contrast analysis revealed no significant difference between NUE for 45 and 90 kg N ha^{-1} ($P = 0.20$; Table 1.6). This was also the case for NUE at 45 and 135 kg N ha^{-1} ($P = 0.41$) as well as NUE difference between the N rates of 90 and 135 kg N ha^{-1} ($P = 0.64$).

Similar to N rate, N placement time had no effect on NUE in 2019 ($P = 0.11$; Table 1.5). However, applying N at FK_5 had the largest effect with an NUE of 22.9% (Figure 1.5). Nitrogen placement 7 and 30 days before planting had the effect of lowering NUE. At these placement times, NUE was 2.3 and 7.3% lower than NUE achieved by placing N at FK_5 (Figure 1.5). Single degree of freedom contrast was performed to further assess whether differences existed among treatment levels. Results showed a significant difference between NUE recorded when N was applied at FK_5 and 30 days before planting ($P = 0.03$; Table 1.6). No such a difference was obtained between N applied 30 and 7 days prior to planting ($P = 0.18$), and between N applied 7 days before planting and at FK_5 ($P = 0.41$) (Table 1.6).

For the 2020 winter wheat harvest, there was no significant NUE response to the interaction between time and rate of N application ($P = 0.36$) (Table 1.5). Similarly, main effects, time and rate of N application, did not influence winter wheat NUE ($P \geq 0.08$; Table 1.5). Evaluation of the effect of rate of N application using a single degree of freedom contrast resulted in similar NUE values. The NUE difference between N applied at 45 and 90 kg ha^{-1} was not statistically significant ($P = 0.56$). The same result was observed for contrasts between 45 and 135 kg N ha^{-1} ($P = 0.44$) and 45 and 90 kg N ha^{-1} ($P = 0.86$). However, NUE was highest (24.7%) for N applied at a rate 45 kg ha^{-1} (Figure 1.4). The lowest NUE, 21.1%, was achieved by applying 135 kg N ha^{-1}.

In 2020, time of N application showed a significant effect when evaluated using a single degree of freedom contrast (Table 1.6). This significant difference in NUE occurred between N applied 30 and 7 days prior to planting ($P = 0.03$; Table 1.6), and N applied 30 days prior to planting and at FK_5 growth stage ($P = 0.03$). Applying N 7 days before planting and at FK_5 resulted in similar NUE values of approximately 25.1% ($P = 0.99$) (Figure 1.5). This reduced to about 15.6% for N applied 30 days before planting.

1.4.4. Nitrogen Use Efficiency, Efaw

In 2019, winter wheat grain NUE was similar for the different combinations of interaction between N rates and placement time ($P = 0.71$; Table 1.5). Further investigation of main effects showed that N application rates did not significantly affect NUE ($P = 0.53$; Table 1.5). This was further corroborated by single degree of freedom contrast that showed no NUE difference between N applied at 45 and 90 kg ha^{-1} ($P = 0.98$; Table 1.6). The NUE achieved by applying 45 and 135 kg N ha^{-1} did not differ significantly from each other ($P = 0.34$). Similarly, no such a difference was revealed for NUE at 90 and 135 kg N ha^{-1} application rates ($P = 0.33$). Nitrogen applied at the rate of 45 and 90 kg ha^{-1} had the largest NUE of 24.5 and 24.6% respectively (Figure 1.4). These NUE values reduced by 3.7 and 3.8% respectively after applying 135 kg N ha^{-1} was (Figure 1.4).

Time of N application also had no significant effect on NUE for grain winter wheat in 2019 ($P = 0.27$; Table 1.5). Nevertheless, an NUE of 26.8% attained at FK_5 was higher than NUE obtained with N applied 7 and 30 days prior to planting (Figure 1.5). This NUE value exceeded NUE for N applied 7 and 30 days prior to planting by 4.4 and 6.1 respectively. Performing a single degree of freedom contrast did not yield any significant difference between NUE reported for N applied 7 and 30 days before planting ($P = 0.65$), 30 days before planting and at FK_5 ($P = 0.11$), and 7 days and FK_5 ($P = 0.25$) (Table 1.6).

Similar to 2019, the interaction between time and rate of N application had no significant effect on NUE in 2020 ($P = 0.46$; Table 1.5). There was also no effect of N rate on NUE ($P = 0.55$; Table 1.5). Applying N at 45 kg ha^{-1} resulted in NUE of 20.3%. Meanwhile, N applied at 90 and 135 kg ha^{-1} led to similar NUE values of approximately 15.5% (Table 1.5). Single degree of freedom contrast did not show any NUE difference between the N rate of 45 kg N ha^{-1} to 90 kg ha^{-1} ($P = 0.44$; Table 1.6; Figure 1.5). A corresponding result was realized for NUE achieved by contrasting 45 kg N ha^{-1} to 135 kg N ha^{-1} ($P = 0.43$), and 90 kg N ha^{-1} to 135 kg N ha^{-1} ($P = 0.99$) (Table 1.5).

Application of N at different time had no major impact on NUE in 2020 ($P = 0.48$) (Table 1.5). Single degree of freedom contrasts between N applied 30 and 7 days before planting, N applied 30 days before planting and at FK_5, and N applied 7 days before planting and at FK_5 indicated similar NUE values ($P \geq 0.55$; Table 1.6). Despite the lack of differences, applying N at FK_5 resulted in an NUE of 19.1% and exceeded NUE achieved by applying N 7 and 30 days before planting by 2.8 and 3.5% respectively (Figure 1.5).

1.5. Discussion

1.5.1. Grain yield

Improving grain yield and NUE requires an understanding of the nature of the interaction between several environmental variables that influence wheat production. In 2019, this study found a significant effect of the interaction between rate and time of N application on winter wheat grain yield at Efaw. This implies that applying N to achieve a realistic yield target also depended on the time at which N was applied. Alternatively, yield response to time of N application was also a function of N rate. However, time and rate of N application did not interact to impact winter wheat grain yield in 2020 at Efaw and Lahoma as well as Lahoma in 2019. This is an indication that neither synergistic nor antagonistic interaction took place to influence wheat grain yield. The results at Efaw (2019) agreed with work done by Zebarth and Sheard (1992) and Woodard and Bly (1998) that found the interaction between time and rate of N application to have a significant effect on winter wheat grain yield. Our study found grain yield to be larger when 135 kg N ha^{-1} was applied at FK_5. Abedi et al. (2011) reported that the interaction between time and rate of N application led to larger grain yield at higher N rates. However, their work also showed that in some cases grain yield began to decline as the rate of application exceeded 240 kg N ha^{-1}. This is because N influences wheat grain yield in a quadratic pattern as excess N may become toxic to crop plants (Si et al., 2020). The interaction was possibly because of the loss of some of the N applied preplant while those applied in-season could have been taken up by plants resulting in different grain yield slopes (Figure 1.3). Sogbedji et al. (2001) pointed out that with much precipitation, some of the N applied preplant can be lost via denitrification and leaching. This may explain why grain yield for N rates of at least 90 kg ha^{-1} applied at FK_5 was larger than that of N applied preplant at all rates (Table 1.7). However, at lower N rates, preplant N application led to a slightly greater grain yield than N applied in-season. This result at Efaw suggests that determining an appropriate time and rate of N application could improve grain yield for winter wheat.

Nitrogen application rate, as the main effect, was important in determining the yield level attainable in a given crop growing environment. This was the case at Lahoma and Efaw where grain yield increased as the rate of N application was increased. Consequently, grain yield was largest at the N application rate of 135 kg ha^{-1}. In 2 of 4 site-years, N applied at 90 and 135 kg ha^{-1} led to statistically similar grain yield levels. This implies that producers applying 45 kg N ha^{-1} above 90 kg N ha^{-1} may in some years observe a substantial yield benefit. Furthermore, applying at least 90 kg N ha^{-1}, led to yields that exceeded yield levels reached in the unfertilized check plots. Mineralization potential might have been low to supply adequate N to meet crop demand for N, meaning that application of mineral N at the right amount was impactful. Schulz et al. (2015) stated that soil with high mineralization potential and enough plant available water is able to compensate for any potential N deficiency. Because N is one of the most important plant nutrients, its role in improving crop production is well-documented in several studies (Fang et al., 2006; Abedi et al., 2011; Walsh et al., 2018). Nitrogen application leads to larger grain yields by improving yield components such as the number of spikes and number of seeds per spike (Abedi et al., 2011; Si et al., 2020). The yield improvement may take on a quadratic pattern as N rates are increased (Woodard and Bly, 1998; Yang et al., 2017; Russenes et al., 2019; Si et al., 2020), meaning that grain yield begins to decrease at high N rates.

The effect of time of N application on winter wheat grain yield was inconsistent at the two sites and years considered in this study. As such, time of N application was important in 2019 and 2020 at Lahoma and Efaw respectively. Grain yield at Lahoma for N applied at FK_5 was statistically lower than grain yield attained with N applied 7 and 30 days before planting. On average, applying N preplant had a 29.2% higher grain yield than N applied at FK_5 alone. This could be attributed to early season shortage of N affecting proper establishment of yield components. Schulz et al. (2015) noted that time of N application could be important when there is low precipitation in-season to lower uptake of applied N via transpiration stream. Additionally, early season application of N may improve grain yield by increasing winter wheat head density (Weisz et al., 2001). Noteworthy, early season applied N has been observed to lead to more tillers and high leaf area index that allow wheat crops to transpire and assimilate more organic materials (Johnston and Fowler, 1992). However, wheat crops that did not receive preplant N may be able to compensate for early season N deficiency by increasing the number of seeds per head as well as tillers upon N application in-season (Brown et al., 2005). Raun et al. (2002) reported that the yield potential of a given growing environment may not be maximized without application of some N preplant. This may explain why grain yield was lower for N applied at FK_5 as plants lacked adequate supply of N to promote early season growth. Without adequate supply of N, early season deficiency is likely to occur leading to competition that may cause the death of some tillers (Efretuei et al., 2016). Where possible, active optical sensors or other high-tech approaches for N management should be adopted (Arnall and Mullen, 2011). Alternatively, high rate of N applied in-season may cause lodging and lead to a reduction in grain yield (Brown et al., 2005). However, the increased likelihood for the loss of N applied early before planting via leaching and or denitrification (Sogbedji et al., 2001; Delgado, 2002) is an important consideration that should not be ignored when making decisions regarding the best time to apply N. In Lahoma (2019), in-season N was applied in March 2020 and this coincided with a period when rainfall increased from less than 30 mm in February to more than 300 mm in May (Figure 1.6). This could have favored denitrification, leaching and volatilization resulting to the loss of applied N intended for crop use.

At Efaw (2020), applying N before planting lowered grain yield when compared to in-season N application. This corresponded with results reported by Vaughan et al. (1990) that for fall-applied N to achieve the same yield level as spring-applied N, 20% more N applied in spring has to be added to the fall-applied N. This indicates that applying N after planting may result in more grain yield than N applied preplant. In comparison to preplant N application time, Boyer et al. (2012) showed that an additional 100 kg of wheat grain yield could be generated by applying 90 kg N ha^{-1} in-season. In addition, N placement in-season provides the nutrient at the time when it is most needed by the wheat crop (Raun et al., 2002). Lower grain yield associated with early season applied N may be attributed to leaching and denitrification of NO_3^- (Delgado, 2002; Beaudoin et al., 2005).

In 2020 at Lahoma, yield response to time of N application was insignificant, an indication that yield levels were similar across N application timings. If N loss is less for preplant and in-season applied N, then the probability of having similar grain yields increases (Schulz et al., 2015). At this site (2020), rainfall received was fairly consistent throughout the growing season that the slope over time appears to be near zero (Figure 1.6). This could have led to similar losses of N for the different N application times leading to similar grain yields. In addition, N was potentially supplied from the soil to mitigate early season N deficiency that could have created the yield difference between preplant and in-season applied N or the crop plants were able to recover from any early season deficiency (Efretuei et al., 2016).

Similar to the observation at Lahoma in 2020, Boman et al. (1995) detected no dramatic yield differences between N applied preplant and after planting. They, however, stated that N applied in-season could lead to plant tissue damage and suggested that the appropriate time to apply N is in early January (late FK_3). Furthermore, early season deficiency may occur if N application is delayed until midseason and this needs to be corrected if yield potential for any growing environment is to be realized (Fowler and Brydon, 1989).

At all sites and years, N applied 7 and 30 days before planting resulted in similar grain yields. In theory, this suggests that one can choose to apply N at any of these two preplant timings.

However, the likelihood of N loss may be higher with N applied 30 days before planting. As such, potential losses via leaching, denitrification and or volatilization (Sogbedji et al., 2001; Fang et al., 2006) in very early applied N (preplant) has to be properly weighed against any benefits that arise from such a timing of N application.

Apart from Lahoma in 2019, it was evident that applying N at FK_5 may not lower grain yield and in some years may lead to a substantial grain yield advantage over preplant N application. But because of the interaction that occurred between time and rate of N application at Efaw in 2019, a producer may also wish to consider N rate in decisions regarding when to apply N and the desired production level. This is because the effect of time on winter wheat grain yield also relies on N rate applied.

1.5.2. NUE

Nitrogen use efficiency was evaluated based on both the time and rate of N application. Overall analysis of variance did not reveal a significant effect of time and rate of N application on NUE at both sites. Specifically on timing N application, single degree of freedom contrast indicated that a substantial difference existed between NUE obtained at the N application time of 7 and 30 days prior to planting as well as 30 days and FK_5 in 2020 at Lahoma experimental site. At the same site in 2019, NUE for N applied 30 days prior to planting and at FK_5 were significantly different from each other. It is, therefore, apparent that time of N application plays a vital role for the increased recovery of N in the grain. A dissimilar observation was made at Efaw where time did not influence NUE in both years. Generally, applying N at FK_5 led to larger NUE values than those associated with N applied prior to planting. Nitrogen applied at FK_5 had at least 4.2% larger NUE value than N applied preplant. This NUE gap was even wider when N applied at FK_5 was contrasted to N applied 30 days before planting. In this case, N applied at FK_5 had between 4.8 and 8.4% higher NUE compared to N applied 30 days before planting. These results agree with observations reported by Dhillon et al. (2019) that topdressing N enhances NUE for winter wheat. They contrasted N applied preplant to N applied as topdress and reported NUE to be significantly different between the two application times in 3 out of 5 site-years with topdressing, on average, producing larger NUE values. Barbieri et al. (2008) also noted that delaying and applying N until at least tillering leads to an improvement in NUE. This is because N applied in-season such as at anthesis leads to increased uptake of N by as much as 12% (Wuest and Cassman, 1992). Splitting and spreading N application at different times also rely on the premise that in-season application improves grain N uptake (Sohail et al., 2018; Dhillon et al., 2019). As such, time in which N is applied may bring double benefits of gaining in grain yield as well as improving NUE and all appeared to favor N applied in-season (Figure 1.5). Considering that applying N 30 days prior to planting lowered NUE, it may be good to delay the application time until when most needed by the crops. Mindful of the fact that giving a small dose of N preplant increases the likelihood of maximizing yield potential, it may be necessary to apply some N before planting (Raun et al., 2002). Potentially, most of the N applied in-season goes to increasing grain N and consequently, grain NUE rather than yield (Brown et al., 2005). Even if not significant, a slight improvement in NUE globally could lead to a massive reduction in the amount of N consumed (Raun and Johnson, 1999). They projected that a 1% increase in NUE could save as much as 489,892 Mg N per annum. This makes time of N application to be one strategy that is important for improving NUE in cereal production that currently stands at about 33% (Raun and Johnson, 1999). Nitrogen use efficiency and grain yield may differ temporally and spatially. We observed differences in NUE achieved with N applied at different times in Lahoma, which was under conventional tillage system with urea broadcast incorporated (for N applied preplant). This was not the case at Efaw, which was under no-till management and urea was broadcast applied without incorporation. It is unclear if no-till played any role for the lack of NUE differences among treatments. However, there can be differences in NUE due to tillage system. For instance, Teal et al. (2007) found NUE under no-till to be on average 7.5% higher than NUE under conventional tillage system. Crop residues retained on the soil surface may reduce N loss via runoff and leaching (Diao et al., 2020). Our study did not evaluate effect of tillage or incorporation/broadcasting of N since these variables did not form part of the same treatment design in the same experiment. Nonetheless, NUE averaged over time appeared to be similar for no-till with surface N broadcast (20.7%) and conventional tillage with surface N broadcast-incorporated (20.2%).

Although there was a significant effect of N rate on grain yield, no such effect was seen on NUE (Table 1.5; Figure 1.1). Lower NUE values were associated with higher rates of N application. This phenomenon has been reported in several studies (Raun et al., 2002; Halvorson et al., 2004). Our work found NUE for N applied at 45 kg ha^{-1} to exceed NUE applied at 135 kg ha^{-1} by 3.2% (Lahoma) and 4.2% (Efaw) when averaged over years for each site. Halvorson et al. (2004) evaluated NUE under no-till for several years and reported NUE that range from 46 to 86% for N applied at 112 and 28 kg N ha^{-1} respectively. Lack of a significant interaction between rate and time of N application was also observed in this study, consistent with results reported by Barbieri et al. (2008). Since grain yield was significantly affected by N application and in particular, at rates that equaled or exceeded 90 kg N ha^{-1}, it is possible that much of the applied N went to improving grain yield rather than grain N recovery. Lollato et al. (2019) observed that grain N concentration decreases as grain yield increases because of starch accumulation in the grain.

1.6. Conclusion

Time and rate of N application may interact to dictate grain yield levels harvested at a specific location in certain years. In this study, an interaction effect was seen at Efaw in 2019 where the largest grain yields were associated with high N rates applied at FK_5. Nitrogen application rate was crucial in determining yield level attained at a specific site in any given year. Grain yield increased as the rate of N application was increased from 0 to 135 kg ha^{-1}. Generally, applying about 90 kg N ha^{-1} resulted in grain yield that exceeded yield levels in the unfertilized check plot by a significant margin. In addition, application of 135 kg N ha^{-1} had an average grain yield of 3.5 Mg ha^{-1} and exceeded that of 45 kg N ha^{-1} by approximately 32.9%. Grain yield contrasted at these two N rates were significantly different in all but one site-year. Time of N application influenced grain yield in an inconsistent manner with yield in some years being similar while others differed significantly. For 4 out of 8 contrasts between N applied 30 days before planting and at FK_5, and N applied 7 days before planting and at FK_5 grain yield were significantly different (Table 1.6). On average, N applied at FK_5 led to 2.3 and 4.3% higher grain yield over N applied 7 and 30 days prior to planting respectively.

Nitrogen use efficiency was not significantly affected by time and rate of N application nor the interaction between the two variables. Applying N at FK_5 led to larger NUE values when compared to N applied preplant. In particular, N applied 30 days prior to planting at Lahoma and evaluated via contrast analysis showed a significantly lower NUE compared to N applied at FK_5. On average, N placement at FK_5 resulted in 23.5% NUE when compared to 16.9% attained with N applied 30 days before planting. Determining an appropriate time and rate of N application is an important consideration that should be integrated in any N management decision necessary to improve wheat grain yield and NUE.

Table 1.1. Treatment structure for evaluating the effect of rates and time of N application on winter wheat grain yield

Treatment	N Source	Quantity of nutrients applied, kg per ha			
		Preplant N		N at Feekes 5	Phosphorus
		30 days[1]	7 days[1]		
1	-	0	0	0	19.6
2	Urea	45	0	0	19.6
3	Urea	90	0	0	19.6
4	Urea	135	0	0	19.6
5	-	0	0	0	19.6
6	Urea	0	45	0	19.6
7	Urea	0	90	0	19.6
8	Urea	0	135	0	19.6
9	-	0	0	0	19.6
10	Urea	0	0	45	19.6
11	Urea	0	0	90	19.6
12	Urea	0	0	135	19.6

[1]7 and 30 days represent the number of days N was applied before planting wheat

Table 1.2. Initial soil chemical properties at Efaw and Lahoma in 2018

Treatment	Efaw[1]					Lahoma[1]				
	K	P	NO_3^-	NH_4^+	pH	K	P	NO_3^-	NH_4^+	pH
1	207	31	5.3	12.0	5.9	225	12	7.6	7.6	6.1
2	217	41	5.1	11.2	5.8	225	11	7.3	7.2	6.3
3	186	30	3.7	12.3	6.0	217	12	5.7	8.5	6.4
4	195	28	4.9	13.6	5.8	211	12	6.5	6.4	6.5
5	197	30	4.7	13.0	6.0	216	10	6.3	6.9	6.5
6	192	33	4.7	13.4	6.0	208	11	5.9	7.3	6.3
7	213	35	4.9	12.1	6.1	221	11	7.3	7.3	6.4
8	208	31	5.3	15.8	6.1	217	12	5.0	10.2	6.5
9	195	33	4.9	12.5	5.9	215	10	5.4	10.0	6.4
10	185	22	4.6	12.9	5.7	211	10	5.7	7.4	6.5
11	181	22	3.9	10.5	5.9	214	11	6.5	10.8	6.5
12	206	34	5.1	12.3	5.9	206	12	6.1	12.4	6.4

[1]Apart from soil pH which is unitless, all the units for soil chemical properties are in mg per kg

Table 1.3. Initial soil chemical properties at Efaw and Lahoma in 2019

Treatment	Efaw[1]					Lahoma[1]				
	K	P	NO_3^-	NH_4^+	pH	K	P	NO_3^-	NH_4^+	pH
1	117	12	13	4.2	6.5	231	12	9	7	5.4
2	116	14	16	4.2	6.2	232	7	8	5	5.8
3	111	16	20	5.0	5.8	229	7	7	6	5.7
4	109	18	17	4.0	6.3	229	7	8	7	5.8
5	109	16	16	4.5	6.2	236	6	8	8	5.9
6	115	19	20	5.3	5.8	229	9	7	6	5.7
7	104	18	18	4.5	5.8	228	11	7	7	5.6
8	113	19	22	5.7	5.9	241	11	7	7	5.7
9	107	18	23	5.7	5.6	229	10	7	8	5.6
10	108	19	21	6.0	6.2	230	8	7	7	5.7
11	111	16	19	8.8	6.1	226	7	7	6	5.8
12	105	19	18	5.3	5.7	226	9	7	8	5.7

[1]Apart from soil pH which is unitless, all the units for soil chemical properties are in mg per kg

Table 1.4. Winter wheat planting and N application dates, and methods of N application at Efaw and Lahoma, OK

Location	Tillage	Date				Method	Days[1]	
		N application		Planting				
		2018	2019	2018	2019		2018	2019
Efaw	No-till	Sep 13	Sep 12	Oct 12	Oct 10	Preplant	29	28
Efaw	No-till	Oct 4	Oct 2	-	-	Preplant	8	8
Efaw	No-till	Mar 22	Feb 21	-	-	Top dress	190	135
Lahoma	CT	Sep 14	Sep 6	Oct 15	Oct 4	Preplant	32	28
Lahoma	CT	Oct 5	Sep 27	-	-	Preplant	10	7
Lahoma	CT	Mar 22	Feb 21	-	-	Top dress	189	141

[1]Indicates the number of days urea was applied prior to or after planting and should be considered together with the column delineating method

Table 1.5. Analysis of variance showing the effect of time and rate of N application on winter wheat grain yield in 2019 and 2020

Sources of Variation	DF[a]	Mean Square[b]				p-value			
		Lahoma		Efaw		Lahoma		Efaw	
		2019	2020	2019	2020	2019	2020	2019	2020
Grain yield									
N Rate	3	2.32	3.58	4.37	0.96	< 0.001	0.006	< 0.001	< 0.001
Time	2	1.45	0.58	0.06	1.3	< 0.001	0.422	0.335	< 0.001
N rate × Time	6	0.08	1.47	0.15	0.18	0.547	0.075	0.027	0.159
NUE									
N Rate	2	48	18.9	41.6	56.7	0.393	0.704	0.529	0.546
Time	2	123.7	169.4	89	68.8	0.109	0.08	0.271	0.484
N rate × Time	4	27.3	63.9	33.4	86.6	0.692	0.357	0.714	0.458

[a] Degrees of freedom. In 2019, yield error DF for Lahoma and Efaw were each 22. For NUE, error DF for both sites were each 16 (2019). In 2020, NUE error DF was 11, and 12 for Lahoma and Efaw respectively.
[b] Yield residual mean squared errors (MSE) for Lahoma and Efaw in 2019 were 0.094 and 0.050 respectively. In 2020, residual MSE for Lahoma and Efaw were 0.650 and 0.106 respectively. For NUE (2019), the residual MSE were 48.5 and 62.8 in Lahoma and Efaw respectively. NUE residual MSE was 52.4 and 89.2 at Lahoma and efaw respectively,

Table 1.6. Single degree of freedom contrasts evaluating grain yield differences as well as NUE differences at specific treatment levels

Contrasts[a]	t-value				p-value			
	Lahoma		Efaw		Lahoma		Efaw	
	2019	2020	2019	2020	2019	2020	2019	2020
Yield								
N rate								
45 vs 90	-1.20	-2.01	-5.64	-0.46	0.23	0.05	< 0.01	0.64
45 vs 135	-3.30	-3.05	-7.79	-1.83	< 0.01	< 0.01	< 0.01	0.08
90 vs 135	-2.09	-1.04	-2.14	-1.37	0.04	0.30	0.04	0.18
Time								
30 vs 7	0.09	-0.64	-0.11	0.32	0.92	0.53	0.91	0.75
30 vs FK_5	2.79	-1.02	-0.48	-2.65	0.01	0.31	0.64	0.01
7 vs FK_5	2.70	-0.38	-0.36	-2.97	0.01	0.70	0.72	< 0.01
NUE								
N rate								
45 vs 90	1.3	0.59	-0.03	0.78	0.2	0.56	0.98	0.44
45 vs 135	0.83	0.79	0.96	0.81	0.41	0.44	0.34	0.43
90 vs 135	-0.47	0.17	0.99	0.01	0.64	0.86	0.33	0.99
Time								
30 vs 7	-1.38	-2.41	-0.46	-0.11	0.18	0.03	0.65	0.91
30 vs FK_5	-2.22	-2.28	-1.65	0.61	0.03	0.03	0.11	0.55
7 vs FK_5	-0.84	0.01	-1.19	-0.45	0.41	0.99	0.24	0.66

[a]N rates are in kg ha^{-1} while N was applied at (time) 30 and 7 days before planting, and at FK_5 growth stage

Table 1.7. Mean grain yield associated with the interaction between rate and time of N application at Efaw in 2019

Treatment Structure		Yield ($Mg\ ha^{-1}$)	SE[2]
N rate ($kg\ ha^{-1}$)	Time[1]		
0	30	2.3	0.1
45	30	3.1	0.1
90	30	3.5	0.3
135	30	3.5	0.2
0	7	2.2	0.3
45	7	2.8	0.1
90	7	3.5	0.3
135	7	3.8	0.1
0	FK_5	2.3	0.1
45	FK_5	2.7	0.3
90	FK_5	3.7	0.1
135	FK_5	4.2	0.3

[1]Indicates number of days N was applied before planting (30 and 7 days) or Feekes growth stage 5 (FK_5)

[2] SE, standard error for grain yield

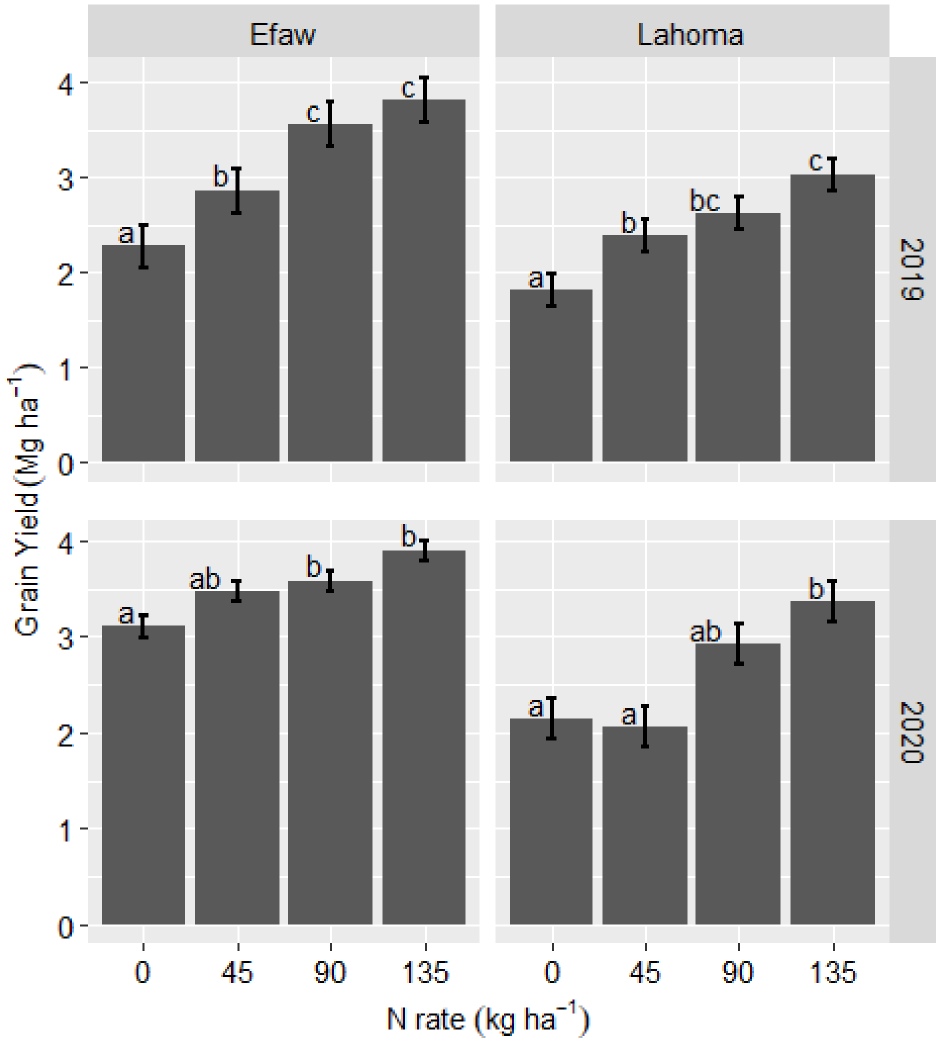

Figure 1.1. Effect of rate of N application on winter wheat grain yield in Efaw and Lahoma experimental sites in 2019 and 2020

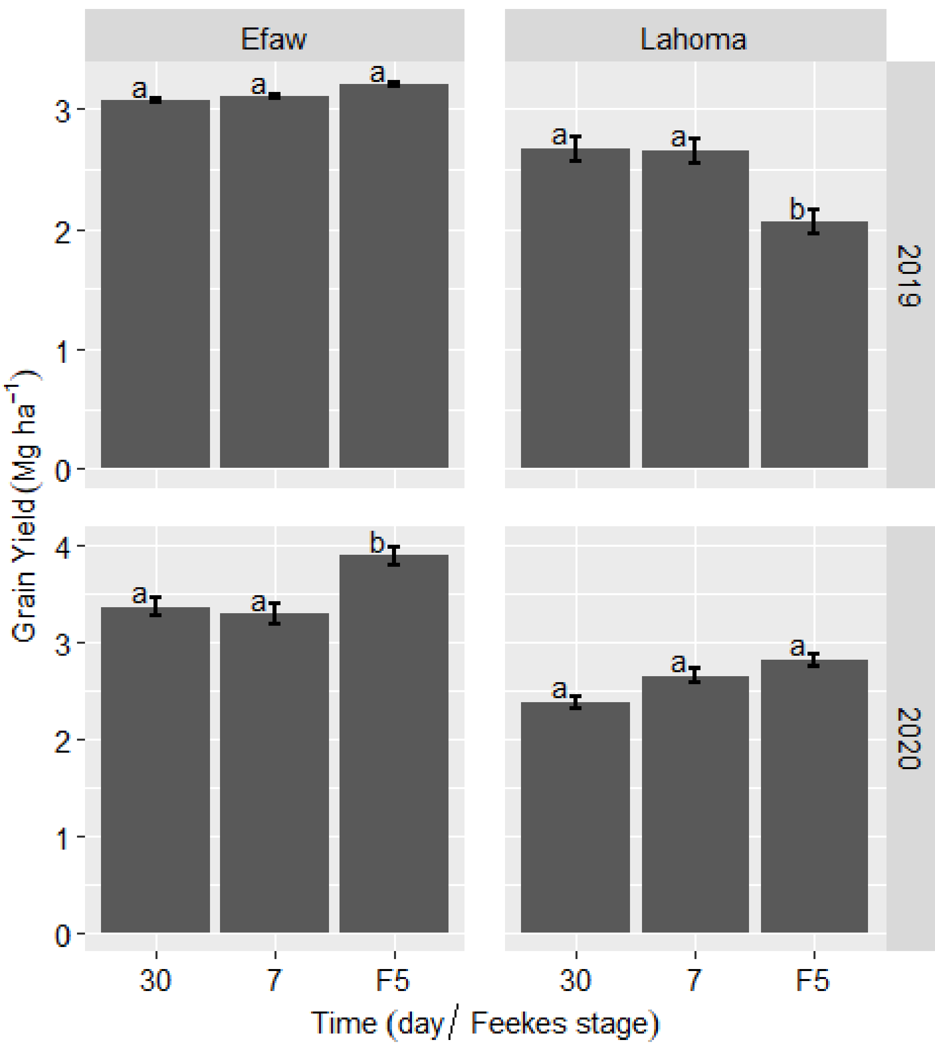

Figure 1.2. Effect of time of N application on winter wheat grain yield at Efaw and Lahoma experimental sites in 2019 and 2020

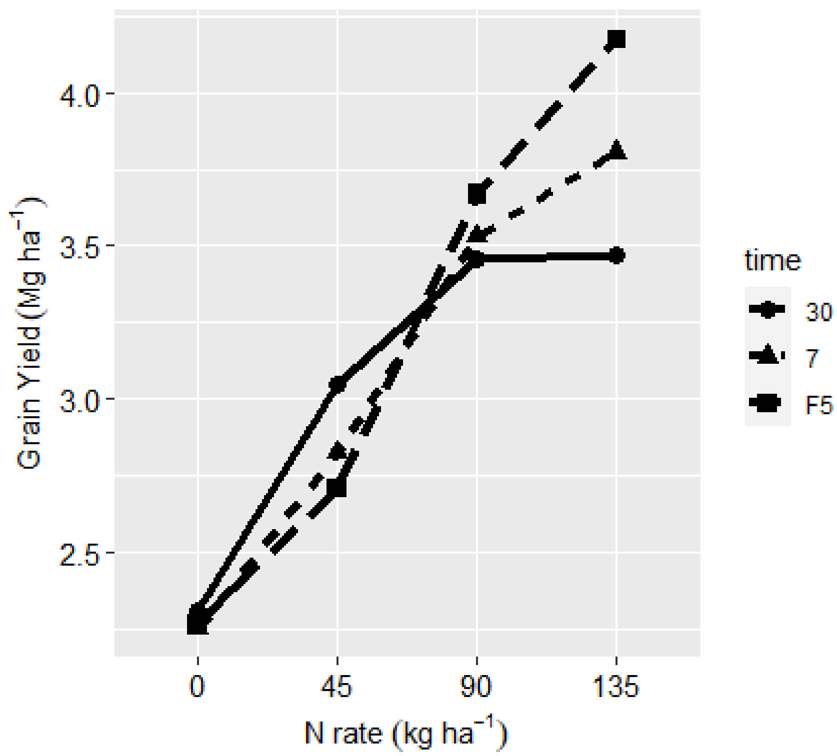

Figure 1.3. Interaction effect of rate and time of N application on wheat grain yield in Efaw in 2019

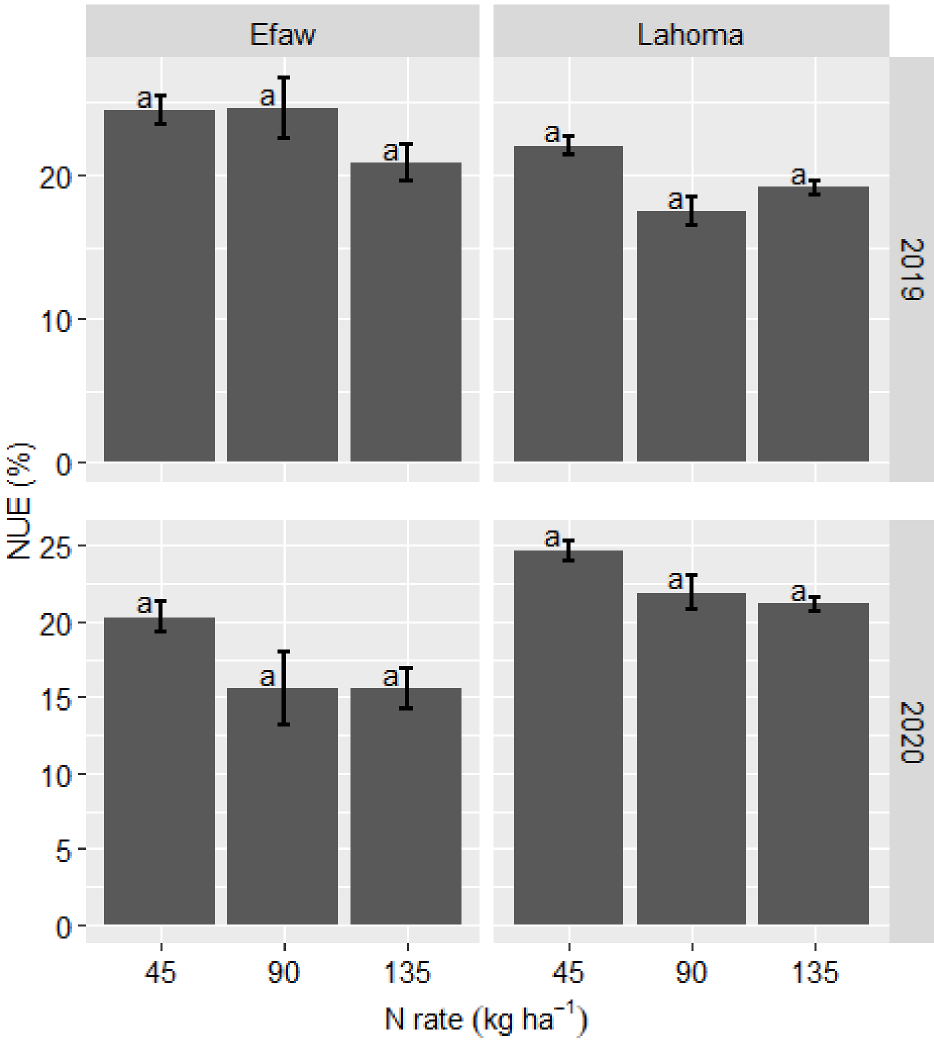

Figure 1.4. NUE for winter wheat as influenced by N in Efaw and Lahoma experimental sites in 2019 and 2020

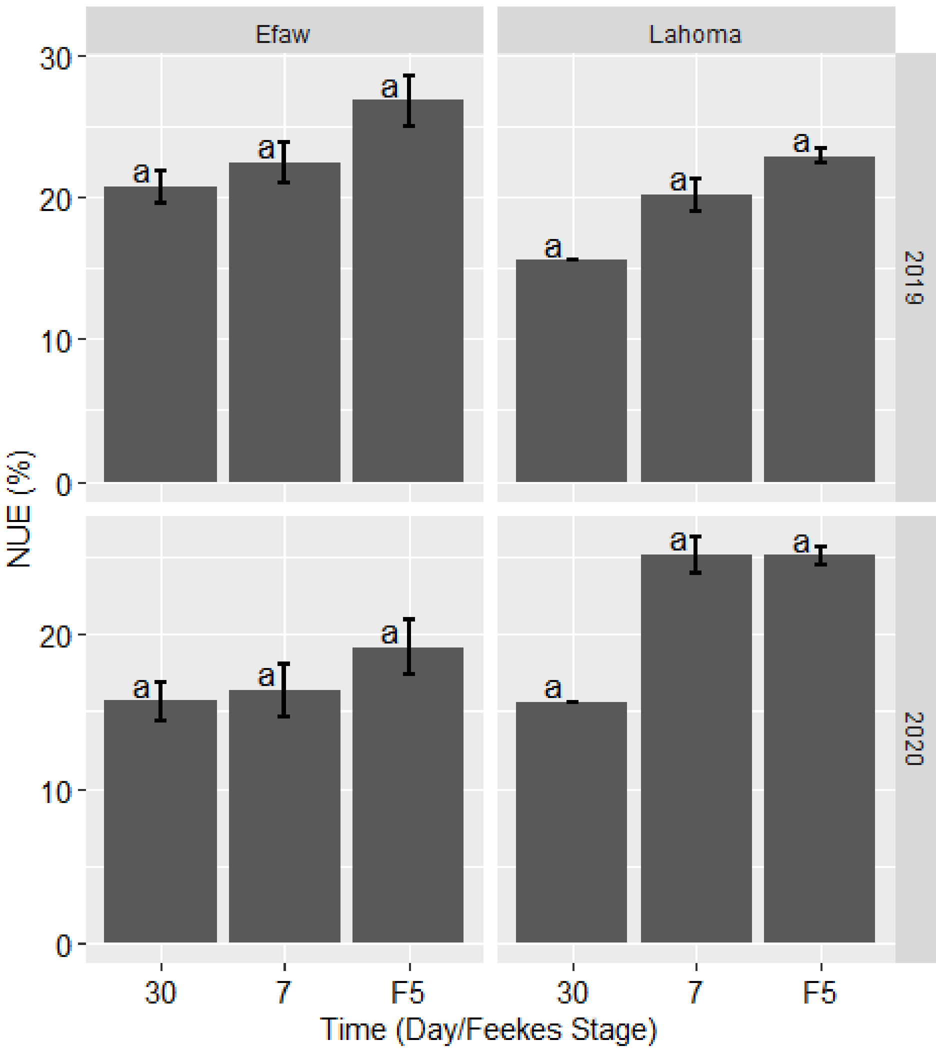

Figure 1.5. NUE for winter wheat as influenced by time of nitrogen application at Efaw and Lahoma experimental sites in 2019 and 2020

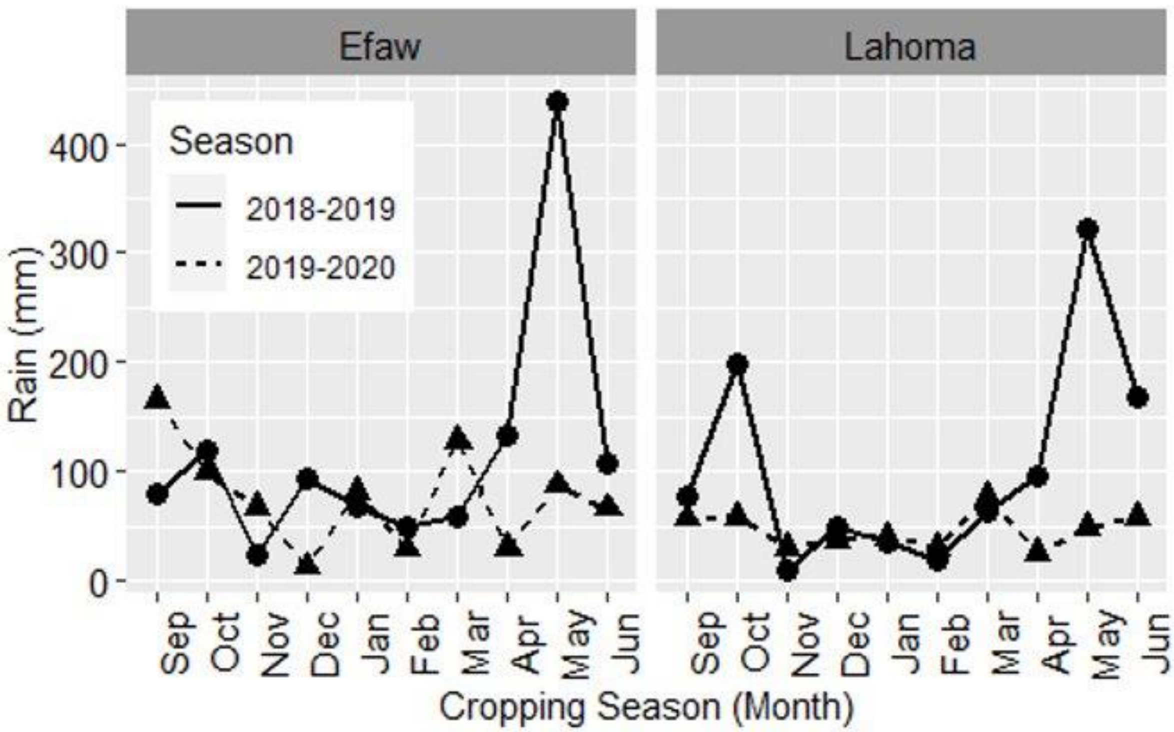

Figure 1.6. Average rainfall during the two crop growing seasons at Efaw and Lahoma

CHAPTER II

WORLD SULFUR USE EFFICIENCY FOR CEREAL CROPS

Abstract

Sulfur (S) is an essential plant nutrient needed for higher crop yields and improved nutritional value. In recent decades, the occurrence of S deficiency has increased and fertilizer S use may steadily increase. This may lead to inefficient crop utilization of S and result in a negative impact on the environment. The objective of this work was to estimate world S use efficiency (SUE) for major cereal crops grown around the world.

A 10-year data set (2005–2014) was obtained from the Food and Agriculture Organization, the US Geological Survey, and an array of other published research articles. Statistical analysis was performed using MS Excel to obtain total area for world and cereal crops, grain yield, and fertilizer S applied. The difference method $\left(\frac{\text{Grain S derived from (Fertilized Soil - Unfertilized Soil)}}{\text{S applied}}\right)$ was used to compute world SUE. Cereal crops included in this study were barley (*Hordeum vulgare* L.), maize (*Zea mays* L.), rice (*Oryza sativa* L.), millet (*Pennisetum glaucum* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), rye (*Secale cereale* L.), and oat (*Avena sativa* L.). Cereal production increased from 2,669 million Mg in 2005 to 3,346 million Mg in 2014.

Sulfur use efficiency for cereal crops was estimated to be 18%. This low SUE may be attributable to S leaching from the soil profile, immobilization, retention in residues, and adsorption. As increased quantities of fertilizer S are likely to be applied in future to meet the ever-growing demand for food, SUE could decline below 18%.

2.1. Introduction

Sulfur (S) is an essential plant nutrient vital for plant growth and development particularly the formation of amino acids and proteins. In agricultural production today, S is ranked by some scientists, producers and industries as the fourth most applied plant nutrient after nitrogen (N), phosphorus (P) and potassium (K) (Messick et al., 2005; TSI, 2018). Zhao et al. (2001) revealed that S is not only important for improved nutritional value of cereal crops but also crop yield. They further noted that deficiency of S may lead to as much as a 50% yield loss in cereals. Similarly, Järvan et al. (2008) demonstrated the importance of S in attaining higher crop yield while comparing plots treated with S to untreated check plots. Their work showed that application of S improved cysteine, methionine, threonine and lysine contents by 24.5, 35.3, 14.4 and 7.7% respectively. Like N, the application of S has been reported to increase crop yield as the rate of application increases (Randall et al., 1981). This yield increase is only up to a certain point above which decline could occur. Randall et al. (1981) reported a yield decline at S rates that equaled or exceeded 50 kg S ha^{-1}.

Furthermore, higher yields are attained when N and S are applied together than with individual nutrients applied alone (Randall et al., 1981; Järvan et al., 2008; ; Järvan et al., 2012; Klikocka et al. 2017). Overall, fertilizer S tends to increase cereal grain yield as the rate of application increases (Xie et al., 2017). This demonstrates the importance of S in cereal production and may justify the continued effort to improve its uptake and utilization by cereal crops.

The past years have seen an increase in the quantities of S used for agricultural purposes from 6.65 million Mg in 2009 to 7.0 million Mg in 2015 (US Geological Survey, 2018). A projection by Heffer and Prud'homme (2016) indicates that the quantity of S consumed by multiple sectors including agriculture will grow at an annual rate of 3% from 58 million Mg in 2015 to 69 million Mg by 2020. This suggests that the level of S application is expected to rise over time. It is even particularly relevant today as soils become increasingly deficient in S due to low industrial S emission, high crop removal, and immobilization (Sutar et al., 2017). The demand for S and other plant nutrients is further expected to increase with the projected 100 to 110% increase in global food demand by 2050 (Tilman et al., 2011). This projected increase in food demand may, in turn, lead to an increase in the environmental fate of S including soil and water acidification.

Several studies have focused on understanding the contribution of S in crop yield and grain quality while some specifically investigated SUE in cereals. When Bharathi and Poongothai (2008) combined both straw and grain S, SUE was found to be between 4.6 and 5.2% and observed that SUE tended to decrease at rates that equaled or exceeded 45 kg S ha^{-1}. They further reported that SUE was much lower when only grain S was considered in the computation of SUE with the highest being 3.1% at a rate of 15 kg S ha^{-1}. A similarly low SUE for millet was reported by Gupta and Jain (2008) where 8.1% SUE for the grain was the highest at 45 kg S ha^{-1}. Haque et al. (2015) also made a similar observation and reported an SUE for rice to be less than 10%. Singh et al. (2014) analyzed S balance and noted that between 11 and 18% of S applied was taken up by wheat. The low SUE could be attributed to leaching of S from the soil profile, immobilization, S retained in the crop residues and adsorbed to clay hydrous oxides of Al and Fe and anion exchange sites (Nor, 1981; Singh et al., 2014). In the same study, it was observed that between 25 to 40% of the applied S could not be accounted for in the soil, crop grain and or residues. It is also worth noting that a lot of S was assimilated in the straw where 22 to 31% of applied S was recovered in rice straw (Shivay et al., 2014).

This low SUE together with 33% NUE (Raun et al., 1999), 16% PUE (Dhillon et al., 2017), and 19% KUE (Dhillon et al., 2019a) for cereals, represents an inefficient use of these macro crop nutrients. With S linked to improved efficiency of N recovery in the grain (NUE), its use in crop production will only continue to grow (Klikocka et al., 2017). This contrasts with the popular reasoning in the mid-twentieth century that most soils in farmlands around the world had adequate S to meet crop needs without external fertilization. This, in turn, was one of the reasons for increased production of high analysis N, P, and K fertilizers containing low to no S (Tabatabai, 1984; Chien et al., 2011). Tabatabai (1984) further revealed a low atmospheric deposition of 0.5 to 10 kg S ha^{-1}. Therefore, soil S alone may be unable to meet the need for high crop yields due to the rapid depletion of soil organic S at a rate higher than that of N (Tabatabai, 1984). The increased use of fertilizer S needs to be equally matched by sound agronomic practices which do not only improve crop yield and quality but also address potential adverse effects on the environment.

Despite numerous research studies on S as a crop nutrient (Sahrawat et al. 2008; Kesli and Adak 2012; Haque et al., 2015), few studies specifically focused on estimating SUE and more so at a global level. As global consumption of S alongside other plant nutrients increases, it is crucial to improve SUE and this necessitates the documentation of the current global estimate. Furthermore, few studies have documented SUE estimates for individual cereal crops at field levels, making it highly necessary to provide an overall SUE estimate that could serve as a benchmark for future improvement of SUE for cereal crops.

The objective of this study was, therefore, to estimate the world SUE for major cereal crops grown around the world.

2.2. Literature Review

2.2.1. Importance of Sulfur in crop production and consumption trend

The central role played by S in amino acid and protein synthesis makes it one of the most important plant nutrients for improving nutritional quality of cereals and other crops. Sulfur is an essential nutrient vital for attaining higher crop yield (Sharma et al., 2007). The Sulfur Institute (TSI, 2018) indicated that alongside N, P, and K, S will be important to meet the level of food production needed to satisfy the human food requirements which are projected to double by 2050.

Besides increasing cereal grain yield as an independent plant nutrient (Calvo et al., 2008), S also improves the uptake of other plant nutrients, most notably uptake of N. Järvan et al. (2008) demonstrated this in an experiment where they found S applied together with N to yield 8-43% more than N applied alone. A similar result was obtained by Klikocka et al. (2016) who observed a 1.3% higher grain yield for wheat when 80 kg N ha^{-1} and 50 kg S ha^{-1} fertilizers were applied together than when 80 kg N ha^{-1} was applied alone. They also reported a significant increase in amino acid contents of wheat particularly methionine that increased by about 14.7%. Nyborg (1968) showed that addition of S in soils with sufficient levels of NPK resulted in a dramatic increase in yield for cereals than when S or NPK were applied separately. In this case, applying S together with NPK produced 1.0 Mg ha^{-1} more grain yield than NPK alone. The improvement in the uptake of N with S application may also improve soil chemical, biological and physical properties. It was shown by Raun et al. (1998) and Aula et al. (2016) that N application resulted in an increase in soil organic carbon. This suggests that N and S applied together may not only increase crop yield but also the quantity of organic C and S returned to the croplands. This was further illustrated by the large quantity of maize residues generated with an increase in S rate which peaked at 60 kg S ha^{-1} (Khan et al., 2006). Nitrogen and S may be released through the process of mineralization and reduce the demand for inorganic N and S. Sulfur has also been observed to increase root mass and length in comparison to S deficient soils (Carciochi et al., 2017). This increase in root mass and length may provide more surface area for uptake of N and other plant nutrients and possibly lead to high yields associated with N and S applied together. Zhao et al. (1999) detected an insignificant decrease in wheat grain protein for each unit increase in S rate. In the same work, a trend for increase in grain S concentration and gel protein weight was observed over the unfertilized check plots.

According to analysis of data from FAO (2018), the global consumption of S fertilizers averaged about 1.4 million Mg per year between 1991 and 2000. Moreover, the FAO reported the amount of S fertilizers consumed globally in 1961 to be around 0.6 million Mg S. In 2016, the global quantity of S fertilizers consumed was estimated to be 2.5 million Mg, a 31% increase in S consumption since 2002. This figure is, however, projected to grow since the global consumption of S for various purposes including agriculture is expected to increase at an annual rate of 3% to reach 69 million Mg by 2020 (Heffer. and Prud'homme, 2016). This is indicative of the growing demand for S fertilizers in agricultural crop fields to match the current high yield levels for cereals due to improved crop agronomic practices and crop genetics (Tilman, 1999; Godfray et al., 2010). Increasing demand for S also increases the likelihood that it might be over applied leading to environmental concerns that documenting SUE becomes paramount.

2.2.2. Review of SUE for cereal crops

Sulfur use efficiency for cereals represents the amount of S applied as fertilizer S that is recovered in the grain. Although a great deal of research has been directed at S as a plant nutrient, few research efforts have been directed towards improving SUE for cereals when compared to the primary plant nutrients. This was possibly due to industrial emission of S which was returned to the soil through precipitation when regulations regarding S emission were not very strong (TSI, 2018). The institute, however, noted that with strict implementation of environmental regulations today, S emission to the atmosphere and deposition to the soil declined, one of the reasons for increased deficiency of S in agricultural croplands. Gupta and Jain (2008) found that little or no application of S can lead to depletion of S in the soil by as much as 32%.

The last few decades have seen a large increase in the quantities of S applied in agricultural crop fields (Pasricha and Abrol, 2003). As the quantity of S applied continues to rise, it becomes necessary to understand and document grain SUE for cereals which are grown on more than 61% of cultivated cropland (Dhillon et al., 2017). While the increase in cereal grain yield and quality is highly invaluable, the potential effect of excess S from fertilizers on the environment particularly acidification of soils and water bodies cannot be underestimated (Brown, 1982). Klikocka et al. (2016) observed that application of S beyond 60 kg ha^{-1} led to a decrease in maize grain yield, an indication of S loss in the system. Shivay et al. (2014) showed in an experimental result for rice that SUE decreased with increasing levels of S fertilizer applied. The study showed that SUE decreased from 10.1 to 8.2% after application of 15 and 45 kg S ha^{-1}, respectively. When they combined S from grain and straw, SUE was between 29.8 and 41.3%, an indication that a relatively large amount of S is retained in the residues. Bharathi and Poongothai (2008) also conducted an experiment with maize and reported a very low grain SUE which decreased from 3.1 to 2.2% at 15 and 45 kg S ha^{-1} of applied S, respectively.

The lack of a global SUE value for major cereal crops is an important gap in literature that this study aims to fill so as to provide a basis for measuring success associated with future SUE improvement.

2.3. Materials and Methods

The global SUE for cereal crops was computed using a 10-year data set (2005–2014) obtained from the FAO (FAO, 2018), the US Geological Survey (US Geological Survey, 2018), and published research articles (Table 2.1 and Table 2.2). Cereal crops used in the study included barley (*Hordeum vulgare* L.), maize (*Zea mays* L.), rice (*Oryza sativa* L.), millet (*Pennisetum glaucum* L.), wheat (*Triticum aestivum* L.), sorghum (*Sorghum bicolor* L.), rye (*Secale cereale* L.), and oat (*Avena sativa* L.). Data mined from the FAO website (http://www.fao.org/faostat/en/#data) included cultivated areas (overall area for all the crops and area specifically under cereals) and grain yield. Additional data for the total quantity of S consumed in crop production was obtained from US Geological Survey websites (https://minerals.usgs.gov/minerals/pubs/commodity/sulfur/index.html#myb) for S consumed in the United States and its territories, and the FAO website for the rest of the world. Applied statistical analysis for the data was performed using MS Excel. Procedures and assumptions made in work done by Raun and Johnson (1999), Dhillon et al. (2017), and Dhillon et al. (2019a) to compute NUE, PUE, and KUE, respectively, were used to determine SUE for major world cereal crops. It is important to note that this study did not investigate agronomic efficiency and partial productivity factor. It focused specifically on determining the quantity of fertilizer S applied that was recovered in the grain. Residual S was assumed to be part of S coming from the soil and future studies may estimate and consider it as S coming from applied fertilizer in the subsequent years. It also relied on the assumption that the quantity of S consumed is equal to the proportion of area under cereal crops divided by global crop production area. Tracking S and other nutrients used to improve soil fertility by crop groups such as cereal, fruit, leguminous, vegetable, and root/tuber crops among others may improve this estimate in future.

Steps taken to compute SUE were as follows:

i. The total area of land under cereal production was divided by the overall area under crop production to obtain the percentage of world cropland under cereal crops.

ii. This percentage was multiplied by the quantity of S applied in agricultural crop fields to determine the amount of S fertilizer applied to cereal crops.

iii. The total quantity of S in the grain for each cereal crop was obtained by multiplying grain yield by the specific S content (%) for each cereal crop shown in Table 2.1.

iv. Using results from published literature, the amount of S in cereal grains derived from the soil was found to average 71.4% (Table 2.2).

v. Total S taken up in the grain (step iii) was multiplied by 71.4% to determine the amount of S coming from the soil.

vi. The amount of S in the grain due to fertilizer S was then obtained by subtracting S coming from the soil (step vi) from total S taken up in the grain (step iii).

vii. Finally, SUE was calculated using the formula for difference equation below

$$\text{SUE} = \frac{\text{Grain S derived from (Fertilized Soil - Unfertilized Soil)}}{\text{S applied}} \times 100\ (\%)$$

Table 2.1. The estimated quantity of S in the grain as a percentage of total grain weight

S/N	Crop	Grain S (%)	Mean S (%)	Source
1	Barley	0.158	0.118	Rogers et al. (2017) †
		0.113		Boila et al. (1993)
		0.083		Sager (2012)
2	Rice	0.167	0.129	Tabatabai (1984)
		0.091		Sager (2012)
3	Wheat	0.144	0.121	Zhao (1999)
		0.117		Singh et al. 2014 §
		0.118		Boila et al. (1993)
		0.128		Randall et al. (1981)
		0.083		Sager (2012)
		0.128		Moss et al. 1981
		0.128		Shobana et al. (2013)
4	Rye	0.094	0.082	Boila et al. (1993)
		0.069		Sager (2012)
5	Oat	0.140	0.132	Wang et al (2002) ¶
		0.123		Boila et al. (1993)
6	Maize	0.100	0.100	Steele (1981)
		0.100		Divito et al. (2013) #
7	Sorghum	0.095	0.173	Sahrawat et al. (2008) †† ‡‡
		0.250		Zaparrart and Salgado (1994)
8	Millet	0.162	0.161	Stabursvik and Heide (1974)
		0.160		Shobana et al. (2013)

†, §, ¶, # and †† Reported soil organic carbon (SOC) as 4.4, 4.6, 16.4, 25.4 and 3.7 g kg^{-1}, respectively. The rest of the articles did not present SOC for the study sites. In some cases, soil organic matter (SOM) was converted to SOC using; SOM = 0.35 + 1.8 × SOC (Ranney, 1969) and focus was within 0-30 cm soil depth.

‡‡ SOC was got from Rego et al. (2007) as referenced by this source (Sahrawat et al., 2008) that provided grain S.

Table 2.2. The proportion of S (%) in the grain due to S derived from fertilizer and soil

Source	Crop	SOC ($g\ kg^{-1}$)	S Rate ($kg\ ha^{-1}$)	Grain S ($kg\ ha^{-1}$)		Straw S ($kg\ ha^{-1}$)		Grain S composition (%)		SUE (%)
				Fer†	Con‡	Fer	Con	Soil§	Fertilizer	
Bharathi and Poongothai (2008)	Maize	NA ¶	15	4.4	3.9	9.8	9.6	89.3	10.7	4.6
			30	4.8	3.9	10.3	9.6	82.1	17.9	5.2
			45	4.9	3.9	10.8	9.6	80.2	19.8	4.8
Ram et al. (2014)	Rice	4.7	30	5.9	4.8	8.3	6.5	80.3	19.7	9.7
			60	6.5	4.8	8.7	6.5	73.8	26.2	6.4
Shivay et al. (2014)	Rice	5.4	15	6.4	4.9	14.1	9.4	76.4	23.6	41.3
			30	7.4	4.9	16.4	9.4	66.7	33.3	31.5
			45	8.4	4.9	19.3	9.4	58.3	41.7	29.8
Rahman et al (2008)	Rice	8.7	10	4.9	3.7	5.0	4.0	75.8	24.2	21.8
			20	6.0	3.7	6.1	4.0	61.3	38.7	52.1
Islam et al. (2016)	Rice	10.8	15	7.6	5.4	10.3	7.4	70.9	29.1	33.8
			20	6.8	5.4	11.8	7.4	79.3	20.7	29.0
Singh et at. (2014)	Wheat	4.6	15	4.0	3.3	8.4	7.1	82.5	17.5	13.3
			30	4.6	3.3	9.4	7.1	71.7	28.3	12.0
			45	5.0	3.3	10.5	7.1	66.0	34.0	11.3
Gupta and Jain (2008)	Millet	1.8	15	3.7	2.7	6.3	4.5	73.4	26.6	18.5
			30	4.9	2.7	8.2	4.5	55.2	44.8	19.7
			45	6.4	2.7	10.4	4.5	42.5	57.5	21.3
Mean								**71.4**	**28.6**	**20.4**

† S uptake from the fertilized (Fer) plots.

‡ S uptake from unfertilized check (Con) plots.

§ Grain S composition due to the soil (%) = $\frac{\text{S uptake in unfertilized check}}{\text{S uptake in fertilized plot}} \times 100$

¶ SOC, soil organic carbon value not available

2.4. Results and Discussion

2.4.1. Sulfur Use Efficiency for Cereal Crops

Results from this study showed that SUE on a global scale for cereals averaged 18% between 2005 and 2014 (Table 2.3). During this period, the highest SUE was observed in 2014 with 22% while the lowest (14%) occurred in 2005 (Figure 2.1). This result showed that the 14% SUE reported in 2005 increased at an annual rate of 0.78% (r^2 = 0.88; Figure 2.1) to the 2014 level. This trend coincided with a 0.11 million Mg annual decrease in the quantity of S applied (r^2 = 0.598; Figure 2.1). In this study, the average quantity of S consumed in the last 5 years (2010–2014) was 8% lower than 5.8 million Mg applied in the initial 5 years (2005–2009). This reduction in the quantity of S applied could have contributed to the increase in SUE over time since grain nutrient use efficiencies tend to be high at lower nutrient rates. Ceccotti et al. (1998) reported a decline in S consumption in the early 1990s due to global economic recession. The economic recession of late 2000s might have also contributed to the decline in S consumption reported in this study. Since 2011, SUE for cereal crops has consistently increased from one year to the next. The average SUE during this period (2011–2014) exceeded the mean SUE for the entire study period by 2%. The average SUE (18%) obtained in this study is lower than the nutrient use efficiency for most macronutrients. Eriksen (2009) made a similar observation and reported a higher SUE of 25% for agricultural crops. In a rice study, Singh Shivay et al. (2014) estimated SUE to be 29.8% following application of 45 kg S ha^{-1}, which was lower than an average of 34.2% SUE for S rates ranging from 15 to 45 kg ha^{-1}. Singh et al. (2014) recovered 11 to 18% of the applied S in wheat grain. However, prior studies reported much lower SUE in cereals. For instance, Bharathi and Poongothai (2008) reported an SUE that averaged just 4.5%. Their study, however, demonstrated that for every 1 kg S applied to maize, there was an increase in grain yield by as much as 36 kg ha^{-1} over the unfertilized check plot. This may suggest that the applied S could be stimulating aboveground growth and playing other vital roles in crop growth and development that may not necessarily be recovered in the grain.

In as much, Carciochi et al. (2017) revealed that S is critical to increase root mass and length, a factor that could provide more surface area for uptake of N, P and other plant nutrients leading to higher yields associated with N and S applied together (Nyborg, 1968; Wang et al., 2006).

The low SUE could also imply that the nutritional quality of cereals such as amino acid contents may be reduced. These amino acids particularly cysteine and methionine are very important for improved grain quality and may constitute as much as 90% of S found in plants (Giovanelli et al., 1980).

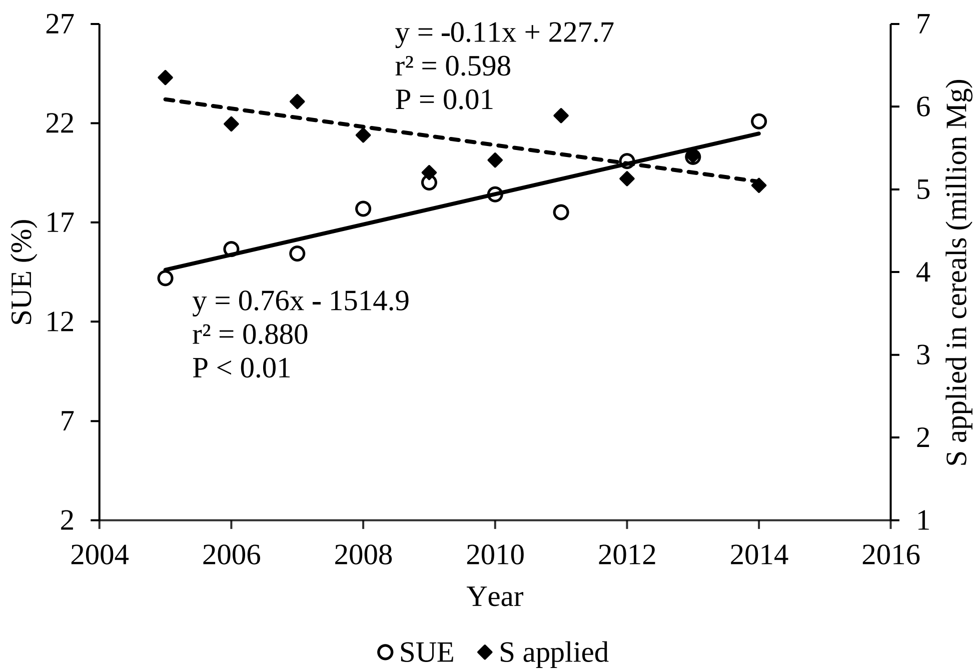

Figure 2.1. Trends for SUE and S consumed by cereal crops in the world

Table 2.3. Estimated average harvested areas, grain yield and sulfur use efficiency for cereal crops for a ten-year period (2005-2014)

Computation	Description	Mean	SE†	Minimum	Maximum
A	Production area for crops (million ha)	1,477	56	1409	1,566
	Cereal production area (million ha)				
	Barley	53	1	48	57
	Maize	199	6	175	223
	Millet	35	1	32	37
	Oats	11	0	9	12
	Rice	190	1	184	196
	Rye	6	0	5	7
	Sorghum	44	1	40	47
	Wheat	243	1	236	250
B	Total	780	11	730	829
C = B/A	Cereal production area (%)	52.8	0.3	51.4	53.9
D	World S application (million Mg) ‡	10.6	0.2	9.7	11.8
E = D × C	S used in cereals (million Mg)	5.6	0.1	5.1	6.4
	Cereal grain yield (million Mg)				
	Barley	142	3	125	157
	Maize	1,032	43	854	1,255
	Millet	31	1	27	36
	Oats	24	1	20	27
	Rice	892	16	816	951
	Rye	16	1	13	19
	Sorghum	63	1	58	71
	Wheat	781	15	716	853
F	Total	2,980	73	2,669	3,346
	S in the grain (million Mg)				
	Barley	0.167	0.004	0.148	0.185
	Maize	1.032	0.043	0.854	1.255
	Millet	0.051	0.002	0.044	0.057
	Oats	0.031	0.001	0.027	0.035
	Rice	1.150	0.021	1.053	1.226
	Rye	0.013	0.001	0.010	0.015
	Sorghum	0.109	0.002	0.101	0.123
	Wheat	0.944	0.019	0.866	1.032
G	Total	3.50	0.08	3.15	3.90
H=G × 71.4%	Grain S-soil (million Mg)	2.50	0.06	2.25	2.79
I =G - H	Grain S-Fertilizer (million Mg)	1.00	0.02	0.90	1.12
J= I/E	SUE (%)	17.9	0.8	14.2	22.1

† Standard error

‡ The quantity of sulfur consumed was estimated from http://www.fao.org/faostat/en/#data, https://minerals.usgs.gov/minerals/pubs/commodity/sulfur/index.html#myb

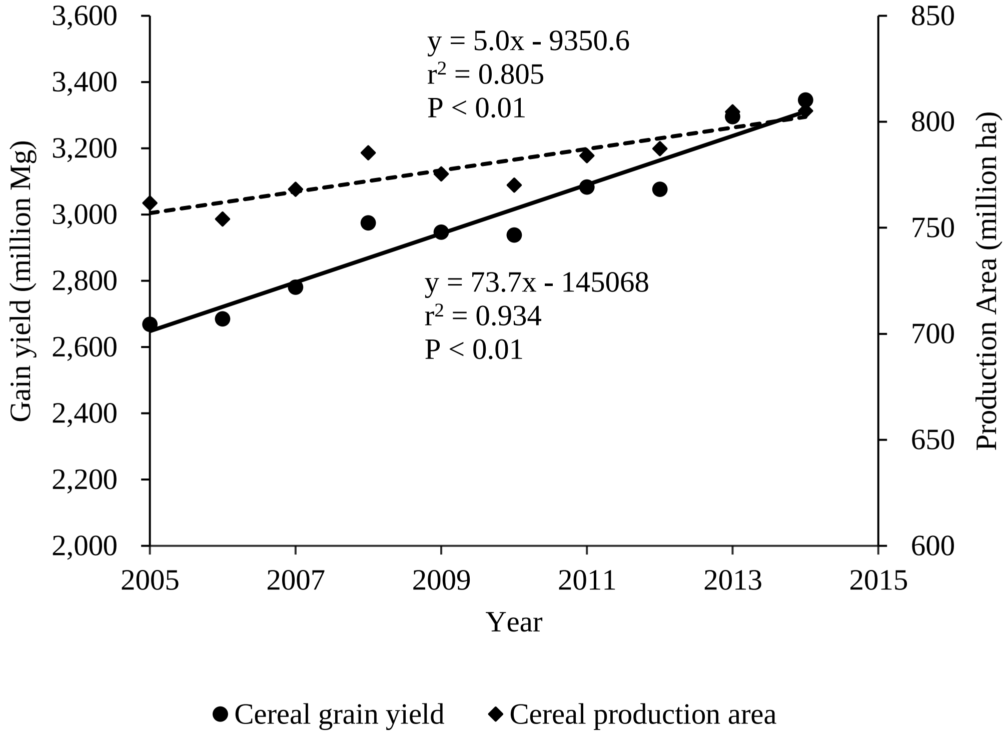

Figure 2.2. World cereal production area and grain yield from 2005 to 2014

Overall, SUE from published articles averaged 20.4% (Table 2.2), a figure which is slightly higher than the world SUE estimate (18.0%) for cereals computed in this study. The difference may be because SUE in published literature was based on field level experiments as opposed to metadata used in the global SUE computation. The difference in SUE may also be attributed to the limited sources of S that FAO (2018) tracked from member nations. Additionally, it may also be due to the fact that SUE may be site- and crop-specific, as is the case for most nutrients.

From 2005 to 2014, the average amount of fertilizer S used to produce all the crops was 10.6 million Mg while the quantity specifically applied to cereals was 5.6 million Mg (Table 2.3). This demonstrated that 53% of S was used in cereal production. An SUE of 18.0% indicated that only 1.0 million Mg of the total S applied for cereal crop production could be recovered in the grain.

During the 2005-2014 study period, area under cereal crop production increased at an annual rate of 5 million ha (Figure 2.2). This might have contributed to the annual grain yield increase of 74 million Mg (Figure 2.2). A 5.7% increase in cereal harvested area was accompanied by a 25.4% increase in cereal grain yield in 2005 over the 2014 level. However, the increase in grain yield may partly be due to crop genetic improvement and increased quantity of plant nutrients applied (Ortiz-Monasterio et al., 1997). The decrease in soil S, due to low atmospheric S deposition resulting from the reduction in industrial S emission, has led to a deficiency of S in some agricultural croplands (TSI, 2018). This deficiency of S may lead to the application of more S in the soil to match the increasing cereal grain yield observed in his study. This further indicates that the 71.4% of applied fertilizer S (Table 2.2 and Table 2.2) that was not recovered in the grain may increase if the rate of application is increased. However, with an adequate understanding of the mechanism for S loss and taking appropriate actions, high crop yield may be achieved alongside improving SUE.

2.4.1. Approaches for Sulfur Use Efficiency Improvement

A holistic approach may be necessary to adequately manage the different S loss pathways. Proper S management needs a comprehensive understanding of soil S cycling that affects the short and long-term ability of the soil to supply S (Schoenau and Malhi, 2008). Because leaching is the major pathway for S loss (Eriksen and Askegaard, 2000; Singh et al., 2014), strategies that address as much may lead to a substantial improvement in S uptake by crops and subsequently improve SUE. Leaching of S from the soil profile is primarily due to the repulsion of SO_4–S from soils and soil organic matter that are predominantly negatively charged (Scherer, 2001; Chien et al., 2011). The amount of S leached from the soil profile depends on a number of factors including mineralization of organic matter and the quantity and time of S application. Ercoli et al. (2012) found an increase in the amount of S leached from 13 to 19 kg ha^{-1} when 60 and 120 kg S ha^{-1}, respectively was applied.

The amount of S leached increases with an increase in the amount of rainfall received (Girma et al., 2005; Ercoli et al., 2012). Furthermore, leaching of S was favored in sandy soils compared to those containing higher quantities of clay (Scherer, 2001). Additionally, aluminum and iron oxides reduce the availability of sulfate through specific adsorption (Ensminger, 1954; Edwards, 1998). Sulfur adsorption and precipitation greatly depend on soil pH. At soil pH greater than 7, an insignificant amount of S is adsorbed as opposed to acidic soil with high quantities of iron and aluminum oxides (Schoenau and Malhi, 2008). Maintaining optimum pH would, therefore, be vital in improving SUE for cereal crops. This may be achieved by raising soil pH in an acidic condition to reduce adsorption and precipitation, and through lowering of pH in an alkaline soil to reduce deep leaching losses. Since SO_4^{2-} is not strongly adsorbed to Al and Fe in comparison to ortho-phosphates (PO_4^{3-}), application of soluble P fertilizers will increase the amount of SO_4^{2-} in soil solution for crop absorption (Kovar and Grant, 2011).

Since crops grown on soil with low soil organic matter content and coarse texture are likely to experience S deficiency (Franzen and Grant, 2008), response to applied S may be observed. However, with more precipitation there is an increased likelihood of S leaching and adopting practices that improve soil organic matter may support in ameliorating this loss pathway. This may include use of no-till and/ or animal manure to increase soil organic carbon content, an important constitute of soil organic matter (Arshad et al. 1990; Guo et al., 2016). By minimizing soil disturbance, the loss of soil organic matter associated with conventional tillage (Balesdent et al., 2000; West and Post, 2002) is reduced.

Ercoli et al. (2012) demonstrated that S loss could be managed by the application of S at the time it will most likely be taken up by crops. Degryse et al. (2018) provided further evidence to illustrate the importance of time of S application by showing that leaching has a more profound effect on plant available S in fall than spring. They revealed that only 16% of S applied to maize could be found within a 90 cm soil depth for fall-applied fertilizer S compared to 50% of spring applied S. Correct time of application coupled with the right fertilizer S source may lead to an improvement in SUE. Chien et al. (2011) stated that fertilizer S such as ammonium sulfate which becomes readily available soon after application might be more effective if applied to plants at the time it is most needed. Slow release fertilizer S such as elemental S may need to be applied well ahead of the intended crop growth stage for it to be transformed by microorganisms to SO_4^{2-} in time to meet the crop demand for S. Indeed, elemental S has been observed to be an effective way to limit leaching of S to lower soil depths (Friesen, 1991; Girma et al., 2005), but that must be oxidized to SO_4^{2-} prior to being assimilated by the plant.

However, some studies have reported limited yield improvement based on time and method of S application in wheat (Dhillon et al., 2019b) and maize (Bullock and Goodroad, 1989; Rehm, 1993). Friesen (1991) noted that recovery of most of the S within 105 cm soil depth does not necessarily mean they are available for crop uptake and indicated that about 40% of the residual S was not within the root zone for plant absorption. Measurement of extractable S, especially from the subsoil, was found to be significant in determining possible S fertilizer response (Bullock and Goodroad, 1989). This is vital for estimating the amount of S to apply as crops may access S leached to subsoil and any early season deficiency may be corrected later through root extension to deeper soil layers.

Some studies suggested volatilization as one of the pathways for S loss in the soil (Minami and Fukushi, 1981; Solberg et al., 2003). This loss can occur in waterlogged soil when SO_4^{2-} is reduced to dimethyl sulfide, a volatile S compound (Banwart and Bremner, 1976). Noteworthy is that this pathway has been reported to lead to an insignificant S loss in anaerobic environments (Campbell, 1998).

In past decades, substantial research has been directed at improving NUE, and that led to the development of a sensor-based technology which accurately estimates N requirements mid-season (Raun et al., 2002). Moreover, a relationship has long been established between N and S that an N/S ratio of 12–15:1 is needed to achieve high crop yield (Stewart and Porter, 1969). Therefore, mid-season sensor-based N recommendations could potentially be used to estimate S requirement for crops based on the above ratio. Recently, Dhillon et al. (2019b) encouraged preplant soil sampling before making any decisions to apply S. Nonetheless, care has to be taken since this method does not accurately predict atmospheric S addition to the soil (Kovar and Grant, 2011). Combining soil testing and sensor-based recommendation would ensure fertilization at the right rate and time. This may also be vital in improving low SUE associated with higher rates of S application observed by Ercoli et al. (2012).

Havlin et al. (2016) noted immobilization of available S during decomposition of crop residue with a wide C/S ratio (> 400:1). This temporarily reduces S availability for crop uptake as microbes use whole or part of the applied mineral S to allow them breakdown the residues. Alternatively, immediate net mineralization and increased S content is associated with decomposition of S-rich residue with narrow C/S ratio (< 200:1) (Schoenau and Malhi, 2008).

2.5. Conclusion

This study estimated SUE for cereal crops grown around the world to be 18.0%. This may serve as a yardstick upon which improvement of SUE for cereal crops can be based. If the current increase in cereal grain yield observed in this study is to be sustained without depleting soil S reserves, then there is a likelihood that more S should be applied. Without deliberate efforts to improve S uptake, this may in turn lower SUE for cereals. Our understanding of the loss pathways for S has grown over the years and adopting best agronomic practices is vital to improving cereal SUE and subsequently reducing the negative impact on the environment. Agricultural researchers and producers could deploy a wide range and combination of approaches that integrate the 4R concept of right; time, rate, source, and placement to improve SUE. This may include evaluating the potential for mid-season sensor-based technology that would lead to accurate estimates of cereal S needs based on the relationship between N and S.

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VITA

Lawrence Aula

Candidate for the Degree of

Doctor of Philosophy

Dissertation: IMPROVING WINTER WHEAT GRAIN YIELD AND NITROGEN USE EFFICIENCY USING NITROGEN APPLICATION TIME AND RATE

Major Field: Soil Science

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Soil Science at Oklahoma State University, Stillwater, Oklahoma in December, 2020.

Completed the requirements for the Master of Science in Plant and Soil Science at Oklahoma State University, Stillwater, Oklahoma in 2014.

Completed the requirements for the Bachelor of Science in Agriculture at Gulu University, Gulu, Uganda in 2009.

Experience:

Graduate Research Assistant-Department of Plant and Soil Sciences, Oklahoma State University, 2018 to 2020

Professional Memberships:

American Society of Agronomy