**World Sulfur Use Efficiency for Cereal Crops**

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**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 into negative footprints on the environment. The objective of this work was to estimate world fertilizer sulfur use efficiency (SUE) for major cereal crops grown around the world. A ten-year data set (2005-2014) was obtained from the Food and Agriculture Organization, the United States 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 [( 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 M Mg in 2005 to 3,346 M 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%.

**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 has not only improved the nutritional value of cereal crops but also crop yield. Deficiency of S may lead to a substantial yield reduction by as much as 50% in cereals (Zhao et al., 2001).

Similarly, Järvan et al. (2008) noted the importance of S in attaining higher crop yield while comparing plots treated with S to untreated check plots. Like N, the application of S has been reported to increase crop yield as the rate of application increases (Randall et al., 1981). However, a decline in yield was observed at rates equal to or greater than 50 kg S ha-1 (Randall et al., 1981).

Furthermore, higher yields are attained when N and S are applied together (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 up to a certain limit (Ying-xin et al., 2017). In contrast, a study conducted by Dhillon et al. (2019b) did not detect a significant response to applied S and attributed this to the adequate supply of S from the mineralization of soil organic matter.

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 (U.S. 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. Therefore, the level of S application is expected to rise 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 increase in global food demand (Tilman et al., 2011). This coupled with S derived from other sources may 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 have specifically investigated SUE in cereals. When Bharathi and Poongothai (2008) combined both stover 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.

However, SUE was much lower when only grain S was considered in the computation with the highest being 2.9% at a rate of 30 kg S ha-1 (Bharathi and Poongothai, 2008). Similarly, low SUE for millet (*Pennisetum glaucum* L.) was reported by Gupta and Jain (2008) where 8.1% for the grain was the highest SUE at 45 kg S ha-1. Haque et al. (2015) also made a similar observation and reported SUE for rice (*Oryza sativa* L.) 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 (*Triticum aestivum* L.). The low SUE could be attributed to leaching of S from the soil profile, S retained in the crop residues and adsorbed to clay hydrous oxides and anion exchange sites (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% nitrogen use efficiency (NUE) (Raun et al., 1999), 16% phosphorus use efficiency (PUE) (Dhillon et al., 2017), and 19% potassium use efficiency (KUE) (Dhillon et al., 2019a) for a range of cereals, represents an inefficient use of these macronutrients. 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 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; Pagani et al., 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 necessary to provide an assessment that could serve as a benchmark for future improvement of SUE for cereal crops.

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

**Materials and Methods**

The global SUE for cereal crops was computed using a ten-year data set (2005-2014) obtained from the Food and Agriculture Organization (FAO, 2018), the United States Geological Survey (U.S. Geological Survey, 2018) and published research articles (Table 1 and Table 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 U.S. 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 analyses 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 in a given year. Residual S was assumed to be part of S coming from the soil and future studies may integrate this in SUE computation. 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:

1. 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.
2. 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. The specific S content (%) for each cereal crop (Table 1) was multiplied by the cereal grain yield to obtain the quantity of grain S taken up by each crop.
3. Using results from published literature, the amount of S in cereal grains derived from the soil/environment was found to average 71.4% (Table 2).
4. Total S taken up in the grain was multiplied by 71.4% to determine the amount of S coming from the soil/environment.
5. The amount of S in the grain due to fertilizer S was then obtained by subtracting S coming from the environment from total S taken up in the grain.
6. Finally, SUE was calculated using the formula below

(Equation 1)

**Table 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) |

**Table 2. The proportion of S (%) in the grain due to S derived from fertilizer and soil**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Source | Crop | 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 | 15 | 4.4 | 3.9 |  | 9.8 | 9.6 |  | 89.3 | 10.7 | 4.6 |
| Maize | 30 | 4.8 | 3.9 |  | 10.3 | 9.6 |  | 82.1 | 17.9 | 5.2 |
| Maize | 45 | 4.9 | 3.9 |  | 10.8 | 9.6 |  | 80.2 | 19.8 | 4.8 |
| Ram et al. (2014) | Rice | 30 | 5.9 | 4.8 |  | 8.3 | 6.5 |  | 80.3 | 19.7 | 9.7 |
| Rice | 60 | 6.5 | 4.8 |  | 8.7 | 6.5 |  | 73.8 | 26.2 | 6.4 |
| Shivay et al. (2014) | Rice | 15 | 6.4 | 4.9 |  | 14.1 | 9.4 |  | 76.4 | 23.6 | 41.3 |
| Rice | 30 | 7.4 | 4.9 |  | 16.4 | 9.4 |  | 66.7 | 33.3 | 31.5 |
| Rice | 45 | 8.4 | 4.9 |  | 19.3 | 9.4 |  | 58.3 | 41.7 | 29.8 |
| Rahman et al (2008) | Rice | 10 | 4.9 | 3.7 |  | 5.0 | 4.0 |  | 75.8 | 24.2 | 21.8 |
| Rice | 20 | 6.0 | 3.7 |  | 6.1 | 4.0 |  | 61.3 | 38.7 | 52.1 |
| Islam et al. (2016) | Rice | 15 | 7.6 | 5.4 |  | 10.3 | 7.4 |  | 70.9 | 29.1 | 33.8 |
| Rice | 20 | 6.8 | 5.4 |  | 11.8 | 7.4 |  | 79.3 | 20.7 | 29.0 |
| Singh et at. (2014) | Wheat | 15 | 4.0 | 3.3 |  | 8.4 | 7.1 |  | 82.5 | 17.5 | 13.3 |
| Wheat | 30 | 4.6 | 3.3 |  | 9.4 | 7.1 |  | 71.7 | 28.3 | 12.0 |
| Wheat | 45 | 5.0 | 3.3 |  | 10.5 | 7.1 |  | 66.0 | 34.0 | 11.3 |
| Gupta and Jain (2008) | Millet | 15 | 3.7 | 2.7 |  | 6.3 | 4.5 |  | 73.4 | 26.6 | 18.5 |
| Millet | 30 | 4.9 | 2.7 |  | 8.2 | 4.5 |  | 55.2 | 44.8 | 19.7 |
| Millet | 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.

**Results and Discussion**

**Sulfur use efficiency for cereal crops**

Results from this study showed that S use efficiency (SUE) on a global scale for cereals averaged 18% between 2005 and 2014 (Table 3). During this period, the highest SUE was observed in 2014 with 22% while the lowest (14%) occurred in 2005 (Figure 1).

This trend coincided with a slight decrease in the quantity of S applied. In this study, the average quantity of S consumed in the last five years (2010-2014) was 8% lower than 5.8M Mg applied in the initial five years (2005-2009). Overall, the quantity of S applied and area under cereal crop production remained relatively unchanged when compared to grain yield and SUE for cereal crops (Figure 1). 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 slight 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, 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.

**Table 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 1. SUE, S consumed, area and grain yield for cereal crops for a ten-year period (2005-2014)

Increased root mass and length provides more surface area for uptake of N and other plant nutrients leading to higher yields associated with N and S applied together (Wang et al., 2006). The benefit of applying S and N together was further demonstrated by Klikocka et al. (2016), who observed a significantly higher content of cysteine and methionine in the grain compared to N applied without S. These amino acids make up nearly 90% of S found in plants (Giovanelli et al., 1980).

Overall, SUE from published articles averaged 20.4%, a figure which is slightly higher than the world SUE estimate (18.0%) for cereals computed in this study (Table 2). 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 10.6M Mg while the quantity specifically applied to cereals was 5.6M Mg (Table 3). This demonstrated that 53% of S was used in cereal production. An SUE of 18.0% indicated that only 1.0M Mg of the total S applied for cereal crop production could be recovered in the grain.

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 be more 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 this study. This further indicates that 82.0% of applied fertilizer S 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.

**Approaches for SUE 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 SO4-S from soils and soil organic matter that are predominantly negatively charged (Scherer, 2001). The amount of S leached from the soil profile depends on a number of factors including mineralization of organic matter, 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, aluminumand 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 SO42- is not strongly adsorbed to Al and Fe in comparison to ortho-phosphates, application of soluble P fertilizers will increase the amount of SO42- in soil solution for crop absorption (Kovar and Grant, 2011).

The primary means by which plants absorb S from the soil is as SO42- (Chien et al., 2011). However, SO42- being negatively charged can easily be lost from negatively charged soil and sandy soil. 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 SO42- 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 SO4-2 prior to being assimilated by the plant.

However, limited yield improvement has been recorded 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).

Some studies suggested volatilization as one of the pathways for S loss in the soil (Minami and Fukushi, 1981; Solberg et al., 2003). 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., 2011; Raun et al., 2017). 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 got 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).

Furthermore, there are additional benefits of applying N and S together in a season where there is crop response to S. According to Randall et al. (1981), application of N and S together in the same field may not only be essential to improve crop yield but also the S concentration in the grain. This suggests that SUE may be enhanced when fertilizer S is applied together with N. This is consistent with work that documented the positive effects of applying N and S together particularly at high N rates (Weil and Mughogho, 2000). Tabatabai, (1984) and Havlin et al. (2016) revealed that application of residues with low C:S ratio increased the availability of S which would otherwise be immobilized by microorganisms. Furthermore, Havlin et al. (2016) noted immobilization of available S during decomposition of crop residue with a wide C:S ratio (> 400:1). 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). Conventional tillage results in faster loss of soil organic matter (Balesdent et al., 2000; West and Post, 2002) and hence can reduce S and the long-term fertility of the soil. Therefore, adoption of cropping systems which result in reduced nutrient losses and increased soil organic matter would be beneficial in improving soil S supply in a year that favors mineralization and lessen the quantity of fertilizer S application.

**Conclusions**

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.

**References**

Balesdent, J., C. Chenu, and M. Balabane. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53:215-230.

Bharathi, C., and S. Poongothai. 2008. Direct and residual effect of sulphur on growth, nutrient uptake, yield and its use efficiency in maize and subsequent greengram. Res. J.Agric. Biol. Sci. 4:368-372.

Boila, R.J., L.D. Campbell, S.C. Stothers, G.H. Crow, and E.A. Ibrahim. 1993. Variation in the mineral content of cereal grains grown at selected locations throughout Manitoba. Can. J. Anim. Sci. 73:421-429

Bullock, D.G., and L.L. Goodroad. 1989. Effect of sulfur rate, application method, and source on yield and mineral content of corn. *Commun. Soil. Sci. Plant Anal.*, 20:1209-1217. https://doi.org/10.1080/00103629009368145

Campbell, L.C. 1998. Managing soil fertility decline. Journal of crop production. 1:29-52.

Carciochi, W.D., G.A. Divito, L.A. Fernández, and H.E. Echeverría. 2017. Sulfur affects root growth and improves nitrogen recovery and internal efficiency in wheat. J. Plant Nutr. 40:1231-1242.

Ceccotti, S.P., R.J. Morris, and D.L. Messick. 1998. A global overview of the sulphur situation: industry’s background, market trends, and commercial aspects of sulphur fertilizers. In: Schnug E. (eds) sulphur in agroecosystems. Nutrients in ecosystems, vol 2. Springer, Dordrecht.

Chien, S.H., M.M. Gearhart, and S. Villagarcía. 2011. Comparison of ammonium sulfate with other nitrogen and sulfur fertilizers in increasing crop production and minimizing environmental impact: a review. Soil Sci. 176:327-335.

Degryse, F., R.C. da Silva, R. Baird, T. Beyrer, F. Below, and M.J. McLaughlin. 2018. Uptake of elemental or sulfate-S from fall-or spring-applied co-granulated fertilizer by corn—A stable isotope and modeling study. Field Crops Res. 221:322-332.

Dhillon, J., G. Torres, E. Driver, B. Figueiredo, and W.R. Raun. 2017. World phosphorus use efficiency in cereal crops. Agron. J. 109:1670-1677.

Dhillon, J.S., E.M. Eickhoff, R.W. Mullen, and W.R. Raun. 2019a. World Potassium Use Efficiency in Cereal Crops. Agron. J. 0. doi:10.2134/agronj2018.07.0462

Dhillon, J.S., S. Dhital, T. Lynch, B. Figueiredo, P. Omara, and W.R. Raun. 2019b. In season application of nitrogen and sulfur in winter wheat (*Triticum aestivum* L.). Agro. Geosci. Env. DOI:10.2134/age2018.10.0047

Divito, G.A., H.R. Sainz Rozas, H.E. Echeverría, N. Wyngaard. 2013. Long-term sulfur fertilization: Effects on crops and residual effects in a no-till system of Argentinean pampas. Commun. Soil. Sci. Plant Anal. 44:1800-1813.

Edwards, P.J. 1998. Sulfur cycling, retention, and mobility in soils: a review. Newtown Square, PA: US Department of Agriculture, Forest Service, Northeastern Research Station.

Ensminger, L.E. 1954. Some factors affecting the adsorption of sulfate by Alabama soils 1. Soil Sci. Soc. Am. J. 18:259-264.

Ercoli, L., I. Arduini, M. Mariotti, L. Lulli and A. Masoni. 2012. Management of sulphur fertiliser to improve durum wheat production and minimise S leaching. Eur. J. Agron. 38:74-82.

Eriksen, J. 2009. Soil sulfur cycling in temperate agricultural systems. Adv. Agron. 102:55-89.

Eriksen, J., and M. Askegaard. 2000. Sulphate leaching in an organic crop rotation on sandy soil in Denmark. Agric. Ecosyst. Environ. 78:107-114.

FAO. 2018. FAOSTAT, data. http://www.fao.org/faostat/en/#data (accessed on 21 Mar. 2019)

F riesen, D.K. 1991. Fate and efficiency of sulfur fertilizer applied to food crops in West Africa. In alleviating soil fertility constraints to increased crop production in West Africa (pp. 59-68). Springer, Dordrecht.

Giovanelli, J., S.H. Mudd, and A.H. Datko. 1980. Sulfur amino acids in plants. In Amino acids and derivatives (pp. 453-505).

Girma, K., J. Mosali, K.W. Freeman, W.R. Raun, K.L. Martin, and W.E. Thomason. 2005. Forage and grain yield response to applied sulfur in winter wheat as influenced by source and rate. J. Plant Nutr. 28:1541-1553.

Gupta, A.K., and N.K. Jain. 2008. Sulphur fertilization in a pearl millet (*Pennisetum glaucum*)-Indian mustard (*Brassica juncea*) cropping system. Arch. Agron. Soil Sci. 54:533-539.

Haque, M.M, M.A. Saleque, A.L. Shah, J.C. Biswas, and P.J. Kim. 2015. Long-Term Effects of Sulfur and Zinc Fertilization on Rice Productivity and Nutrient Efficiency in Double Rice Cropping Paddy in Bangladesh. Commun. Soil. Sci. Plant Anal. 46:2877-2887. https://doi.org/10.1080/00103624.2015.1104333

Havlin, J. L., S.L.Tisdale, W.L. Nelson, and J.D. Beaton. 2016. Soil fertility and fertilizers: An introduction to nutrient management. 8th ed. Pearson India Education Services, Uttar Pradesh, India

Heffer, P., and M. Prud’homme. 2016. Fertilizer Outlook 2016–2020. In 84th IFA Annual Conference, Moscow, Russia (pp. 1-5).

Islam, A. S., M. S. Rana, M. M. Rahman, M. J. A. Mian, M. M. Rahman, M. A. Rahman, and N. Naher., 2016. Growth, yield and nutrient uptake capacity of rice under different sulphur levels. Turkish Journal of Agriculture-Food Science and Technology 4:557-565. DOI: https://doi.org/10.24925/turjaf.v4i7.557-565.709

Järvan, M., L. Edesi, A. Adamson, L. Lukme, and A. Akk. 2008. The effect of sulphur fertilization on yield, quality of protein and baking properties of winter wheat. Agronomy Research6: 459–469

Järvan, M., L. Edesi, and A. Adamson. 2012. The content and quality of protein in winter wheat grains depending on sulphur fertilization. Acta Agric. Scand.62: 627-636. https://doi.org/10.1080/09064710.2012.683495

Kesli, Y., and M.S. Adak. 2012. Effects of different harvest time and sulfur fertilization on amino acid composition of lentil. J. Plant Nutr. 35:1693-1704. https://doi.org/10.1080/01904167.2012.698350

Klikocka, H., M. Cybulska, and A. Nowak. 2017. Efficiency of fertilization and utilization of nitrogen and Sulphur by spring wheat. Pol. J. Environ. Stud. 26:2029-2036

Klikocka, H., M. Cybulska, B. Barczak, B. Narolski, B. Szostak, A. Kobiałka, A. Nowak, E. Wójcik. 2016. The effect of sulphur and nitrogen fertilization on grain yield and technological quality of spring wheat. Plant Soil Environ. 62:230–236

Kovar, J. L. and C. A. Grant. 2011. Nutrient cycling in soils: Sulfur. Publications from USDA-ARS / UNL Faculty. 1383

Messick, D.L., M.X. Fan, and C.D. Brey. 2005. Global sulfur requirement and sulfur fertiliers. Landbauforschung Völkenrode, 283:97-104

Minami, K. and S. Fukushi. 1981. Volatilization of carbonyl sulfide from paddy soils treated with sulfur-containing substances. Soil Sci. Plant Nutr, 27:339-345.

Moss, H. J., C. W. Wrigley, R. MacRichie, and P. J. Randall. 1981. Sulfur and nitrogen fertilizer effects on wheat. II. Influence on grain quality. Aust. J. Agric. Res. 32:213-226.

Ortiz-Monasterio, R., K. D. Sayre, S. Rajaram, and M. McMahon. 1997. Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. Crop Sci. 37:898-904.

Pagani, A., H.E. Echeverría, F.H. Andrade, and H.R. Sainz Rozas. 2012. Effects of nitrogen and sulfur application on grain yield, nutrient accumulation, and harvest indexes in maize. J. Plant Nutr. 35:1080-1097.

Ram, A., D. Kumar, N. Singh, and A. Anand. 2014. Effect of sulphur on growth, productivity and economics of aerobic rice (Oryza sativa). Indian J. Agron. 59:404-409.

Randall, P.J., K. Spencer, and J.R. Freney. 1981. Sulfur and nitrogen fertilizer effects on wheat. i concentrations of sulfur and nitrogen and the nitrogen to sulfur ratio in grain, in relation to the yield response. Aust. J. Agric. Res., 32: 203-12

Raun, W., B. Figueiredo, J. Dhillon, A. Fornah, J. Bushong, H. Zhang, and R. Taylor. 2017. Can yield goals be predicted? Agron. J.109:2389-2395. https://doi.org/10.2134/agronj2017.05.0279

Raun, W.R., and G.V Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357-363.

Raun, W.R., J.B. Solie, and M.L. Stone. 2011. Independence of yield potential and crop nitrogen response. Precision Agric. 12 :508–518.

Rehm, G.W. 1993. Timing sulfur applications for corn (Zea mays L.) production on irrigated sandy soil. Commun. Soil. Sci. Plant Anal. 24:285-294. https://doi.org/10.1080/00103629309368799

Rogers, C.W., G. Hu, and R. Mikkelsen. 2017. Grain yield, quality, and nutrient concentrations of feed, food, and malt barley. Commun. Soil. Sci. Plant Anal. 48:2678-2686.

Sager, M. 2012. Levels of sulfur as an essential nutrient element in the soil-crop-food system in Austria. Agriculture2: 1-11; https://doi.org/10.3390/agriculture2010001

Sahrawat, K.L., T.J. Rego, S.P. Wani, and G. Pardhasaradhi. 2008. Sulfur, boron, and zinc fertilization effects on grain and straw quality of maize and sorghum grown in semi-arid tropical region of India. J. Plant Nutr*.* 31: 1578–1584

Scherer, H.W. 2001. Sulphur in crop production. Eur. J. Agron. 14:81-111.

Schoenau, J. J., S. S. Malhi 2008. Sulfur forms and cycling processes in soil and their relationship to sulfur fertility. Sulfur: a missing link between soils, crops, and nutrition, Agron. Monogr. 50. ASA, CSSA, SSSA, Madison, WI. p. 1-10. doi:10.2134/agronmonogr50.c1

Shivay, Y.S., R. Prasad, and M. Pal. 2014. Effect of Levels and Sources of Sulfur on Yield, Sulfur and Nitrogen Concentration and Uptake and S-Use Efficiency in Basmati Rice. Commun. Soil. Sci. Plant Anal. 45:2468–2479. https://doi.org/10.1080/00103624.2014.941472.

Shobana, S., K. Krishnaswamy, V. Sudha, N. Malleshi, R. Anjana, L. Palaniappan, V. Mohan. 2013. Finger millet (Ragi, Eleusine coracana L.): a review of its nutritional properties, processing, and plausible health benefits. Adv. Food Nutr. Res. 1-39.

Singh, S.P., R. Singh, M.P. Singh, and V.P. Singh. 2014. Impact of sulfur fertilization on different forms and balance of soil sulfur and the nutrition of wheat in wheat-soybean cropping sequence in taraisoil. J. Plant Nutr. 37:618-632. https://doi.org/10.1080/01904167.2013.867987

Solberg, E.D., S.S. Malhi, M. Nyborg, and K.S. Gill. 2003. Fertilizer type, tillage, and application time effects on recovery of sulfate-S from elemental sulfur fertilizers in fallow field soils. Commun. Soil. Sci. Plant Anal. 34:815-830.

Stabursvik, A. and O.M. Heide. 1974. Protein content and amino acid spectrum of finger millet [Eleusine coracana (L.) Gaertn.] as influenced by nitrogen and sulphur fertilizers. Plant Soil, 41:549-571.

Steele, K.W., S.J. McCormick, N. Percival, and N.S. Brown. 1981. Nitrogen, phosphorus, potassium, magnesium, and sulphur requirements for maize grain production. N. Z. J. Exp. Agric., 9:243-249.

Stewart, B.A. and L.K. Porter. 1969. Nitrogen-Sulfur Relationships in Wheat (Triticum aestivum L.), Corn (Zea mays), and Beans (Phaseolus vulgaris) 1. Agron. J. 61:267-271.

Sutar, R.K., A.M. Pujar, B.N.A. Kumar, and N.S. Hebsur. 2017. Sulphur Nutrition in Maize - A Critical Review. Int. J. Pure App. Biosci. 5: 1582-1596

Tabatabai, M.A. 1984. Importance of sulphur in crop production. Biogeochemistry 1: 45-62

Tilman, D., C. Balzer, J. Hill, and B.L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. PNAS 108: 20260-20264.

TSI. 2018. Sulphur–The Fourth Major Plant Nutrient. https://www.sulphurinstitute.org/fertilizer/ (accessed 27 Oct. 2018)

U.S. Geological Survey. 2018. Sulfur: statistics and information.

https://minerals.usgs.gov/minerals/pubs/commodity/sulfur/index.html#myb

(accessed on 21 Mar. 2019)

Wang, H., Y. Inukai, and A. Yamauchi. 2006. Root development and nutrient uptake. Crit. Rev. Plant Sci. 25:279-301.

Wang, S., Y. Wang, E. Schnug, S. Haneklaus, and J. Fleckenstein. 2002. Effects of nitrogen and sulphur fertilization on oats yield, quality and digestibility and nitrogen and sulphur metabolism of sheep in the Inner Mongolia Steppes of China. *Nutr.* Cycling Agroecosyst. 62:195-202.

Weil, R.R. and S.K. Mughogho. 2000. Sulfur nutrition of maize in four regions of Malawi. Agron. J. 92:649-656.

West, T.O. and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Sci. Soc. Am. J*.* 66:1930-1946.

Ying-xin, X., Z. Hui, Z. Yun-ji, Z. Li, Y. Jia-heng, C. Fei-na, L. Cao, W. Chen-yang, and G. Tian-cai. 2017. Grain yield and water use of winter wheat as affected by water and sulfur supply in the North China Plain. J. Integr. Agric. 16: 614–625

Zaparrart, M.I., and J.M. Salgado. 1994. Chemical and nutrition evaluation of whole sorghum flour (Sorghum bicolor, L. Moench), complementation with bean and milk whey, application in baking. Arch Latinoam Nutr. 44:151-157

Zhao, F.J., M.J. Hawkesford, and S.P. McGrath. 1999. Sulphur assimilation and effects on yield and quality of wheat. J. Cereal Sci. 30:1-17.

Zhao, F.J., S.P. McGrath, M.J. Hawkesford. 2001. Sulphur nutrition and the sulphur cycle. Institute of Arable Crops, Research report 2000–2001.