Published June 13, 2019

World Sulfur Use Efficiency for Cereal Crops

Lawrence Aula, Jagmandeep S. Dhillon, Peter Omara,
Gwendolyn B. Wehmeyer, Kyle W. Freeman, and William R. Raun*

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 10-yr 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 [(Total grain S – grain S derived from the soil)/S applied] 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 2669 M Mg in 2005 to 3346 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%.

Core Ideas

- World sulfur use efficiency for cereal crops is unknown.
- World sulfur use efficiency for cereal crops was estimated to be 18%.
- More precision agriculture research is necessary to improve sulfur use efficiency for cereal crops.
- Reasons for low sulfur use efficiency include sulfur; leaching, adsorption, retention in residues, and immobilization as well as failure to adhere to sound agronomic practices and 4R concepts.

Sulfur 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 N, P, and 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, 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 (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. 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

Published in Agron. J. 111:2485–2492 (2019)
doi:10.2134/agronj2019.02.0095
Available freely online through the author-supported open access option

L. Aula, J.S. Dhillon, P. Omara, G.B. Wehmeyer, W.R. Raun, Dep. of Plant and Soil Sciences, Oklahoma State Univ. Stillwater, OK 74075; P. Omara, Faculty of Agriculture and Environment, Gulu University, Uganda; K.W. Freeman, The Mosaic Company, Plymouth, MN 55441. Received 15 Feb. 2019. Accepted 29 Mar. 2019.
*Corresponding author (bill.raun@okstate.edu).

Abbreviations: KUE, potassium use efficiency; NUE, nitrogen use efficiency; PUE, phosphorus use efficiency; SUE, sulfur use efficiency.

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 and 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 (Singh Shivay et al., 2014).

This low SUE together with 33% nitrogen use efficiency (NUE) (Raun and Johnson, 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 that 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 10-yr data set (2005–2014) obtained from the Food and Agriculture Organization (FAO, 2018), the US Geological Survey (US Geological Survey, 2018), and published research articles (Tables 1 and 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 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

$$\text{SUE (Difference Method)} = \frac{\text{Total grain S} - \text{grain S derived from the soil}}{\text{S applied}} \times 100 \quad [1]$$

RESULTS AND DISCUSSION

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 3). During this period, the highest SUE was observed in 2014 with 22% while the lowest (14%) occurred in 2005 (Fig. 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 5 yr (2010–2014) was 8% lower than 5.8M Mg applied in the initial 5 yr (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 (Fig. 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, 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.

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 et al. (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 et al. (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
Singh 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 Shivay 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.

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

Table 3. Estimated average harvested areas, grain yield and sulfur use efficiency for cereal crops for a 10-yr period (2005–2014).

Computation	Description	Mean	SE†	Minimum	Maximum
A	Production area for crops (million ha)	1477	56	1409	1566
	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	1032	43	854	1255
	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	2980	73	2669	3346
	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	Sulfur use efficiency (%)	17.9	0.8	14.2	22.1

† SE, 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

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

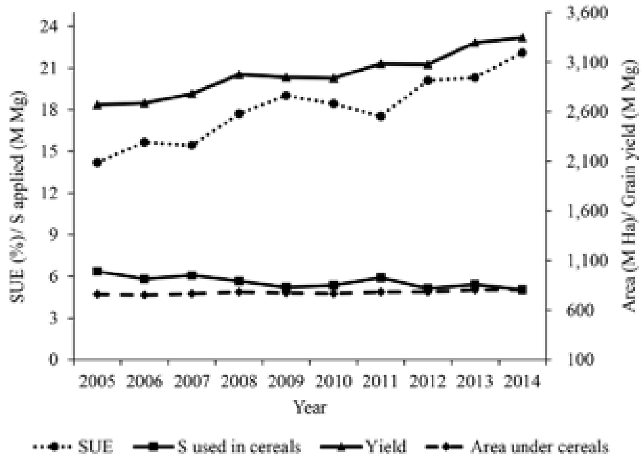

Fig. 1. Sulfur use efficiency, S consumed, area, and grain yield for cereal crops for a 10-yr period (2005–2014).

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 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). 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, application of soluble P fertilizers will increase the amount of SO_4^{2-} in soil solution for crop absorption (Kovar and Grant, 2011).

The primary means by which plants absorb S from the soil is as SO_4^{2-} (Chien et al., 2011). However, SO_4^{2-} 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 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, 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, 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 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 on 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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