**Division – Soil Use and Management | Commission – Soil fertility and plant nutrition**

# Crop Yield Responses to Sulfur Fertilization in Brazilian No-Till Soils: a Systematic Review

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**ABSTRACT:** Sulfur (S) fertilization recommendations for grain crops in Brazil were formerly established from studies on crops with a low yield potential grown on soils under conventional tillage (CT). However, the subsequent adoption of no-tillage (NT) altered S dynamics in the soil, making it necessary to carefully evaluate the applicability of these S fertilizer recommendations. In addition, the emergence of modern high-yield-potential genotypes, the successive application of concentrated low-sulfur fertilizers, and reduction in S atmospheric deposition have raised the likelihood of positive responses of crops to S fertilization. Available literature reports contrasting crop responses to S fertilization in Brazilian soils, ranging from substantial gains to slight yield losses depending on the particular crop, soil, and climate. The primary aim of this study was to examine available data for crop grain responses to S application in NT soils in order to ascertain whether existing recommendations established for Brazilian CT soils also hold for NT soils. A systematic review of data from 35 scientific publications spanning 58 crop harvests revealed a positive yield response to S fertilization in 31 % of the crop harvests, with an average yield increase of 16 %. Crops on soils with available $SO_4^{2-}$-S contents above the critical level (*viz.,* 7.5 mg dm$^{-3}$) exhibited no positive response to S fertilization in any crop harvest ($n$ = 18). Dry edible bean and corn were the most responsive crops, and canola and wheat, the least. For the trials with positive crop responses, a fertilizer rate of 26 kg ha$^{-1}$ S sufficed to obtain at least 95 % of the maximum possible yield. In general, the S fertilization recommendations previously established for CT soil proved effective with grain crops on NT soils as a result of the critical levels of soil available $SO_4^{2-}$-S and the fact that the recommended S rates are similar to those found in this study considering trials conducted under NT conditions only. However, existing recommendations could be improved by using additional criteria for soils with available $SO_4^{2-}$-S contents below the critical level since a positive response was observed in 22 % ($n$ = 18) and 92 % ($n$ = 12) of the crop harvests under a subtropical and a tropical climate, respectively. Our results suggest that S fertilization must be prioritized in NT soils with available $SO_4^{2-}$-S contents below 7.5 mg dm$^{-3}$ in the 0.00-0.20 m layer, especially in tropical climate zones. In addition, regional fertilizer recommendation guidelines should consider crop type and yield expectation in order to facilitate more sustainable S management and increased crop yields in Brazil.

**Keywords:** sulfur fertilizer rate, available $SO_4^{2-}$-S content, climate zone, plant nutrition, sustainable fertilizer management.

# INTRODUCTION

The biogeochemical cycle of S is very complex and involves fluxes in soil, plants, and the atmosphere (Alvarez V et al., 2007). Although atmospheric deposition is a relevant source of S for soil, the amounts of S input it supplies has declined considerably worldwide in recent years as an effect of the implementation of new emission control technologies and more stringent environmental regulations (Divito et al., 2015; Vieira-Filho et al., 2015). In the city of São Paulo, for example, atmospheric deposition decreased twenty-fold from 1985 to 2009 [of 282 to 14 kg ha$^{-1}$ yr$^{-1}$ S (Vieira-Filho et al., 2015)]. In cities distant from large industrial centers and the sea, such as Santa Maria (in the state of Rio Grande do Sul), S was atmospherically deposited at rates ranging from 3.2 to 4.5 kg ha$^{-1}$ yr$^{-1}$ over the periods of 2004/2005 and 2007/2009 (Osório Filho et al., 2007; Tiecher et al., 2013).

Soil contains both organic and inorganic forms of S, the organic form prevailing under tropical and subtropical climates. The balance between the organic and inorganic S pool is governed by redox reactions that are primarily mediated by microorganisms (Rein and Sousa, 2004; Alvarez V et al., 2007; Bissani et al., 2008). In properly aerated soils, sulfate ($SO_4^{2-}$) is the main inorganic S form in the soil solution, which can be taken up by plants (Ercoli et al., 2012) but can also be readily lost by leaching. Organic S constitutes the greatest soil S stock [90-95 % of total soil S (Sutar et al., 2017)]. Its availability to plants depends on the mineralization rate of organic matter (OM), which is in turn influenced by factors such as soil temperature, moisture, aeration, nutrient supply, OM lability, and stoichiometric ratios between nutrients (C:N, C:P, and C:S) (Scherer, 2001; Bissani et al., 2008), as well as by the oxidation state of S in decaying organic matter (Blum et al., 2013). Therefore, the ability of tropical and subtropical soils to fulfill plant S requirements depends on the intensity of the immobilization/mineralization and adsorption/desorption processes (Alvarez V et al., 2007), as well as on whether these processes occur synchronically with the period of highest S demand from plants (Ercoli et al., 2012). Establishing effective S fertilization management recommendations for different soil and climate conditions is thus rather challenging (Scherer, 2001; Bissani et al., 2008).

In Brazil, S deficiencies are largely encountered in sandy soils with low OM content in the Cerrado (tropical savanna) region (Rein and Sousa, 2004). In contrast, the clayey tropical soils and subtropical soils (clay or sandy) rarely require S fertilization to support suitable plant growth (Bissani et al., 2008; CQFS-RS/SC, 2016). Consequently, S is one of the least studied macronutrients in Brazil (Divito et al., 2015; CQFS-RS/SC, 2016) and also in other regions of world (Kihara et al., 2017; Salvagiotti et al., 2017). However, the likelihood of a positive response of grain crops to S fertilization has increased in various ecosystems around the world (Rheinheimer et al., 2005; Ercoli et al., 2011; Blum et al., 2013; Divito et al., 2015; Salvagiotti et al., 2017) as a consequence of (a) higher crop yield potential increasing S plant requirements (Salvagiotti et al., 2017), (b) the repeated use of phosphate and nitrogen fertilizers containing little or no S (Rheinheimer et al., 2005; Osório Filho et al., 2007), (c) reduced S atmospheric deposition (Divito et al., 2015; Vieira-Filho et al., 2015), (d) increased use of monocultures or crop successions, resulting in low inputs of crop residues, and (e) chemical and/or physical constraints on deep-rooting under NT (Dalla Nora et al., 2017). Crop responses to S application in Brazilian NT soils are highly variable and range from substantial increases (Miranda and Miranda, 2008; Fiorini et al., 2016; Pereira et al., 2016; Lopes et al., 2017; Nascente et al., 2017) to slight reductions in grain yield (Barbosa Filho et al., 2005; Megda et al., 2009; Gelain et al., 2011; Rampim et al., 2011) depending on the particular crop, soil, and climate conditions. Therefore, further consideration of these key drivers (*viz.,* climate, soil chemical properties, crop type, and grain yield potential) for crop yield is imperative if management of S fertilization in Brazil is to be more sustainable.

Soil under NT comprises more than 32 Mha in Brazil and NT is the main basis for grain crop production in the country (Febrapdp, 2012). The NT system alters S dynamics

relative to CT (Karlen et al., 2013), in which the soil is periodically tilled and the chemical properties of the arable layer (0.00-0.20 and/or 0.00-0.40 m) are more uniform as a result (Souza et al., 2014). In soils under NT for a long time, surface liming and fertilization applied without soil incorporation increase the nutrient contents and OM in the surface layer, thereby creating a chemical gradient that decreases with increasing depth (Dalla Nora and Amado, 2013; Souza et al., 2014). An increase in soil pH increases the cation exchange capacity, whereas an increase in P content decreases potential sites for sulfate adsorption because phosphate is more readily adsorbed by colloids than sulfate. Therefore, increased content of nutrients in the surface layer of NT soils may induce leaching of sulfate to deeper layers [0.20-0.40 and 0.40-0.60 m (Scherer, 2001; Rheinheimer et al., 2005)]. However, plant root growth in deeper layers may be hindered by the presence of compacted soil and/or chemical restrictions, such as those arising from toxic levels of exchangeable Al or low Ca availability - a common occurrence in NT soils (Lopes et al., 2004; Rein and Sousa, 2004; Dalla Nora and Amado, 2013).

The criteria used to establish official recommendations for S fertilization in Brazil differ among regions. Thus, the recommended S rates for subtropical soils in the states of Rio Grande do Sul and Santa Catarina are based on available $SO_4^{2-}$-S contents (5-10 mg dm$^{-3}$) in the soil surface layer (0.00-0.10 m) and on the specific crop requirements (Bissani et al., 2008; CQFS-RS/SC, 2016). In the state of Paraná, S application is recommended when available $SO_4^{2-}$-S contents in the 0.00-0.20 or 0.20-0.40 m soil layer are below the critical level [6 and 9 mg dm$^{-3}$, respectively (Pauletti and Motta, 2017)]. For tropical soils in the state of São Paulo, S fertilization is recommended when the available $SO_4^{2-}$-S content in the surface layer (0.00-0.20 m) is below 0.05-0.10 mg dm$^{-3}$ (Raij et al., 1997). Recommendations for the Cerrado region (central Brazil) are based on the available $SO_4^{2-}$-S content in the surface (0.00-0.20 m) and subsurface soil layer [0.20-0.40 m (Rein and Sousa, 2004)]. In addition to soil available $SO_4^{2-}$-S, Sfredo et al. (2003) suggest using different critical S levels depending on soil clay content. Nearly all studies from which existing S fertilization recommendations for Brazilian soils have been conducted from the 1970s to the 1990s and on crops with low yield potential grown on CT soil (Lopes et al., 2004; Rein and Sousa, 2004; Bissani et al., 2008; CQFS-RS/SC, 2016; Pauletti and Motta, 2017). It is therefore imperative to revise existing S fertilization recommendations for NT soils bearing high yield potential genotypes in order to identify the need for changes in S fertilization management. In this study, we made a systematic review of existing studies on the topic to compile, summarize, and assess the response of major grain crops to S fertilization in NT soils and to confirm the effectiveness of S fertilizer recommendations for NT soils currently in use in Brazil.

## MATERIALS AND METHODS

### Data compilation

This study was based on data reported in 32 scientific peer-reviewed articles, one technical paper, and two master's degree dissertations dealing with crop yield responses to S fertilization in NT soils in Brazil. The data spanned a total of 58 crop harvests (Figure 1). For this purpose, a search for key words including "sulfur", "elemental sulfur", "ammonium sulfate", "gypsum", "no-tillage system", and "grain yield", and the corresponding terms in Portuguese, was performed in the Web of Science, Science Direct, Scielo, and Google Scholar databases. Any publications meeting one or more of the following criteria were excluded: (a) studies exclusively examining production of biomass, stem, or other vegetative organs; (b) experiments conducted under CT or greenhouse conditions; (c) studies not conducted in Brazil; (d) absence of a control treatment without S fertilization; and (e) trials with fewer than three replications and/or without a random distribution of treatments.

In studies where gypsum, elemental S, or single superphosphate was used as S source, the results were pair-compared with a control treatment (i.e., one without S fertilization) (Table 1). When ammonium sulfate was used as S (and N) source, the results were compared with those of a urea treatment at the same N rate. Finally, when the S source was gypsum, the maximum rate considered was 1 Mg ha$^{-1}$ (equivalent to 160 kg ha$^{-1}$ S) in order to mitigate the confounding effect of higher rates of gypsum - or single superphosphate - as a soil conditioner potentially increasing Ca$^{2+}$ saturation and reducing Al$^{3+}$ activity in subsurface layers.

For each crop harvest, data were categorized in terms of soil properties, environment, and crop specification as follows:

1.  Clay content in the 0.00-0.20 m soil layer: ≤35 % or >35 %, which is the limit between clayey soils and medium textured soils. All studies in this category used the pipette method to determine soil clay content.

2.  Soil OM in the 0.00-0.20 m layer: ≤2.5 % or >2.5 %, which is the limit between the low and medium class (CQFS-RS/SC, 2016).

3.  Available $SO_4^{2-}$-S content in the 0.00-0.20 and 0.20-0.40 m layers: above or below the critical level used by CQFS-RS/SC (2016), which was 5 mg dm$^{-3}$ for low S-demanding crops (corn, wheat) and 10 mg dm$^{-3}$ for high S-demanding crops [soybean, dry edible bean (hereinafter bean), and canola]. All studies stating the extractant for soil available $SO_4^{2-}$-S used calcium phosphate [$Ca(PO_4)_2$]. According to Blum et al. (2014), the $SO_4^{2-}$-S extractants most commonly used in Brazil are $Ca(PO_4)_2$ and $NH_4OAc$ + HOAc, which provide slightly different but highly correlated results ($r = 0.98$) .

4.  pH($H_2O$) in the 0.00-0.20 m soil layer: ≤5.5 or >5.5, which is the limit for recommending application of lime to NT soils bearing grain crops (CQFS-RS/SC, 2016). When soil pH had been measured in a $CaCl_2$ solution, the reported pH value was increased by 0.7 units to estimate pH in water.

5.  Type of soil: Oxisol (*Latossolo*), Ultisol (*Argissolo*), or Alfisol (*Nitossolo*).

6.  Average crop yield: high or normal - high if it exceeded the average grain yield for the state for a given harvest by more than 30 %, as reported by Conab (2018), or otherwise normal.

7.  Crop: soybean, bean, canola, corn, or wheat.

8.  Climate: subtropical or tropical.

### Data analysis

Grain yields for different crops, regions, and crop harvests were compared by using the equation 1 to calculate a relative yield for each crop harvest in terms of the specific treatment leading to the highest yield as reference (Tiecher et al., 2018):

$$\text{Relative yield of crop harvest (\%)} = \frac{\text{Treatment yield (Mg ha}^{-1})}{\text{Treatment with maximum yield of crop harvest (Mg ha}^{-1})} \times 100 \quad \text{Eq. 1}$$

A potential relationship between the relative yield for each crop harvest and leaf tissue S content was examined for 31 crop harvests reported in 17 studies. The data for studies reporting soil available $SO_4^{2-}$-S contents, which spanned 48 crop harvests for the surface soil layer (0.00-0.20 m) and 34 for the subsurface layer (0.20-0.40 m), were used to construct a calibration curve for soil available S from the initial available $SO_4^{2-}$-S content for the experiment and the relative crop yields of the plots receiving no S (controls) (CQFS-RS/SC, 2016; Vieira et al., 2016). The S rate recommended to obtain 95 % of the highest relative yield, which was considered to be the maximum economic efficiency (MEE), was determined by plotting the relative yield of each S
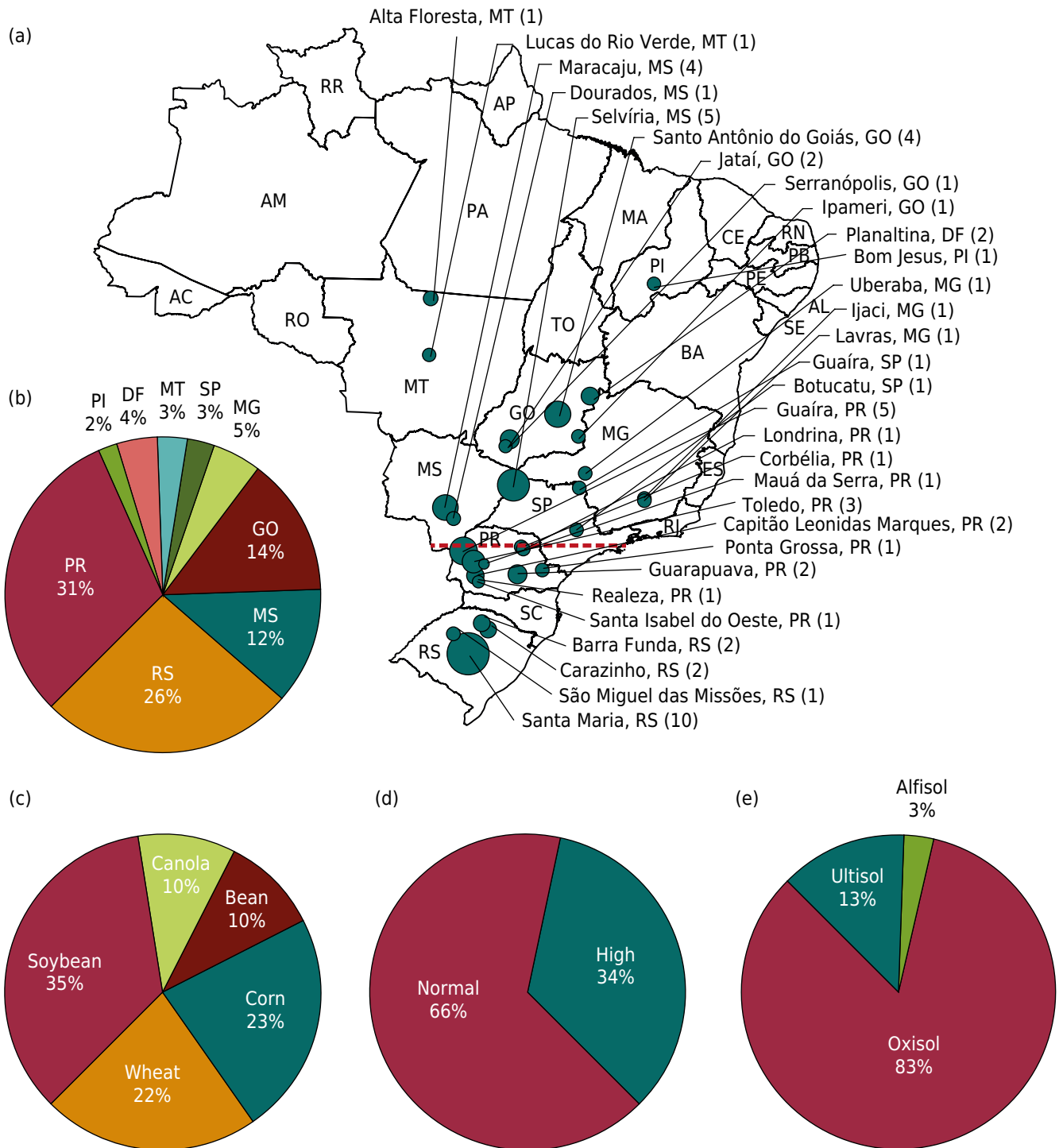
**Figure 1.** Geographic distribution of crop harvests in each city (a), relative frequency of crop harvests grouped by Brazilian state (b), by crops produced (c), by crop yield average (d), and by soil types (e) in the studies that evaluated the effects of sulfur fertilization on crop yield in no-till soils in Brazil. A red dashed line delimits the tropical (upper) and subtropical (lower) climate zones. The acronyms of the Brazilian states: PR = Paraná; RS = Rio Grande do Sul; MS = Mato Grosso do Sul; GO = Goiás; MG = Minas Gerais; SP = São Paulo; MT = Mato Grosso; PI = Piauí; and DF = Distrito Federal.

rate and the respective rate used (Tiecher et al., 2018). Crop response curves were obtained by plotting relative yield against S rate and soil available $SO_4^{2-}$-S content (Equation 2), using the software Sigma Plot 12.5 (Systat Software, San Jose, CA, USA).

Relative Yield (%) = Maximum yield (100 %) × (1 – $10^{-bx}$)                           Eq. 2

Crop responses to S fertilization within the factors of variation were evaluated by the difference in proportion procedures based on 4999 replications in Statkey v. 2.0.1

**Table 1.** Summary of the main information from the studies included in this systematic review

| Reference | Crop | Year | Effect[1] | 0 | 15 | 30 | 45 | 60 | - | - | S source |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Sulfur rates (kg ha$^{-1}$) | | | | | |
| Rheinheimer et al. (2005) | Soybean | 2002/03 | ns | 3.26 | 3.00 | 3.10 | - | 3.29 | - | - | SSP |
| Osório Filho et al. (2007) | Bean | 2004/05 | * | 2.60 | 2.64 | 3.01 | - | 3.08 | - | - | SSP |
| Osório Filho et al. (2007) | Wheat | 2005 | ns | 1.72 | 2.07 | 1.96 | - | 1.86 | - | - | SSP |
| Osório Filho et al. (2007) | Soybean | 2004/05 | ns | 1.68 | 2.00 | 1.93 | - | 1.98 | - | - | SSP |
| Osório Filho et al. (2007) | Canola | 2005 | ns | 1.05 | 1.13 | 1.20 | - | 1.09 | - | - | SSP |
| Lucas et al. (2013) | Canola | 2010 | * | 0.83 | 0.89 | 0.92 | - | 0.95 | - | - | SSP |
| Miranda and Miranda (2008) | Corn | 2000/01 | * | 5.62 | 7.46 | 7.73 | 7.78 | - | - | - | Gypsum |
| Miranda and Miranda (2008) | Corn | 2001/02 | * | 5.36 | 5.94 | 6.67 | 7.75 | - | - | - | Gypsum |
| | | | | 0 | 5 | 10 | 20 | 40 | 60 | - | |
| Nascente et al. (2017) | Bean | 2014 | * | 2.68 | - | 3.28 | 3.26 | 3.15 | 2.66 | - | AS |
| Rheinheimer et al. (2005) | Corn | 2002/03 | * | 8.28 | 10.32 | 10.35 | 10.44 | - | - | - | SSP |
| Rheinheimer et al. (2005) | Canola | 2003 | ns | 1.19 | 1.52 | 1.25 | 1.42 | - | - | - | SSP |
| Tiecher et al. (2013) | Wheat | 2007 | ns | 2.39 | 2.38 | 2.24 | 2.45 | - | - | - | Gypsum |
| | | | | 0 | 20 | 40 | 60 | 80 | 100 | 160 | |
| Crusciol et al. (2006) | Bean[2] | 2004 | * | 2.37 | 2.54 | 2.63 | 2.66 | 2.53 | - | - | AS |
| Rampim et al. (2011) | Soybean | 2006/07 | ns | 3.74 | - | - | - | - | - | 3.53 | Gypsum |
| Rampim et al.( 2011) | Soybean[2] | 2006/08 | ns | 2.94 | - | - | - | - | - | 2.86 | Gypsum |
| Rampim et al. (2011) | Wheat[2] | 2006 | ns | 2.30 | - | - | - | - | - | 2.03 | Gypsum |
| Rampim et al. (2011) | Wheat[2] | 2006 | ns | 1.37 | - | - | - | - | - | 1.44 | Gypsum |
| Gelain et al. (2011) | Soybean[2] | 2007/08 | ns | 2.32 | - | - | - | - | - | 2.27 | Gypsum |
| Zandoná et al. (2015) | Corn | 2012/13 | * | 10.39 | - | - | - | 10.98 | - | 11.00 | Gypsum |
| Zandoná et al. (2015) | Soybean | 2012/13 | * | 2.73 | - | - | - | 2.97 | - | 2.97 | Gypsum |
| Dalla Nora and Amado (2013) | Soybean[2] | 2010/11 | ns | 3.78 | - | - | - | - | - | 3.68 | Gypsum |
| Dalla Nora and Amado (2013) | Corn[2] | 2010/11 | ns | 10.69 | - | - | - | - | - | 10.74 | Gypsum |
| Dalla Nora et al (2017) | Wheat[2] | 2012 | ns | 2.28 | - | - | - | - | - | 2.33 | Gypsum |
| Sávio et al. (2011) | Soybean | 2005/06 | * | 1.65 | - | - | - | 1.97 | - | 2.10 | Gypsum |
| Lopes et al. (2017) | Soybean | 2015/16 | * | 1.42 | 1.52 | 1.62 | 1.68 | 1.64 | 1.68 | - | Factor |
| Marchesan et al. (2017) | Soybean | 2012/13 | ns | 3.21 | - | - | - | - | 3.2 | 3.21 | Gypsum |
| Marchesan et al. (2017) | Soybean | 2013/14 | ns | 3.49 | - | - | - | - | 3.50 | 3.52 | Gypsum |
| Neis et al. (2010) | Soybean | 2007/08 | ns | 4.40 | - | - | - | - | - | 4.41 | Gypsum |
| Soares (2016) | Soybean | 2014/15 | ns | 3.00 | - | - | - | - | - | 3.00 | Gypsum |
| Soares (2016) | Corn | 2015/16 | ns | 7.00 | - | - | - | - | - | 7.00 | Gypsum |
| | | | | 0 | 30 | 60 | 90 | 120 | 128 | 180 | |
| Primo et al. (2012) | Soybean | 2009/10 | ns | 4.16 | 4.08 | 4.02 | - | 4.04 | - | 4.19 | $S^0$ |
| Moda et al. (2013) | Soybean[2] | 2005/06 | ns | 2.46 | 2.48 | 2.51 | 2.69 | 2.50 | - | - | Gypsum |
| Frandoloso et al. (2010) | Corn[2] | 2005/06 | ns | 8.48 | 8.69 | - | - | - | - | - | $S^0$ |
| Rampim et al. (2015) | Soybean | 2011/12 | ns | 2.64 | - | - | - | - | 2.77 | - | Gypsum |
| | | | | 0 | 35 | 40 | 42 | 42-$S^0$ | 80 | 80-$S^0$ | |
| Fiorini et al. (2016) | Corn | 2008/09 | * | 7.56 | - | - | 8.68 | 8.45 | - | - | AS |
| Fiorini et al. (2016) | Corn | 2008/09 | ns | 5.49 | - | - | 5.69 | 5.58 | - | - | AS |

Continue

Continuation

| Reference | Crop | Year | [1] | | | | | | | | Source |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fano (2015) | Wheat | 2013 | ns | 1.40 | - | - | - | - | 1.47 | 1.57 | Factor |
| Fano (2015) | Wheat | 2013 | * | 2.02 | - | - | - | - | 2.12 | 2.35 | Factor |
| Fano (2015) | Wheat | 2013 | ns | 1.23 | - | - | - | - | 1.21 | 1.17 | Factor |
| Megda et al. (2009) | Wheat | 2005 | ns | 3.21 | 3.17 | - | - | - | 3.14 | - | AS |
| Megda et al. (2009) | Wheat | 2006 | ns | 3.22 | 3.09 | - | - | - | 3.30 | - | AS |
| | | | | 0 | 27 | 50 | 51 | 68 | - | - | |
| Pereira et al. (2016) | Soybean[2] | 2013/14 | * | 3.43 | - | 4.37 | - | - | - | - | S$^0$ |
| Mendes et al. (2014) | Corn | 2012/13 | ns | 12.31 | - | 12.28 | - | - | - | - | S$^0$ |
| Mendes et al. (2014) | Corn | 2012/13 | * | 12.55 | - | - | - | 13.24 | - | - | S$^0$ |
| Werner et al. (2013) | Canola | 2011 | ns | 2.17 | 2.17 | - | 2.17 | - | - | - | AS |
| | | | | 0 | 23 | 46 | 69 | 92 | 115 | 138 | |
| Kaefer et al. (2014) | Canola | 2009 | ns | 1.23 | 1.23 | 1.23 | 1.23 | 1.23 | 1.23 | 1.23 | AS |
| Kaefer et al. (2014) | Canola | 2010 | ns | 1.31 | 1.31 | 1.31 | 1.31 | 1.31 | 1.31 | 1.31 | AS |
| Prando et al. (2013) | Wheat | 2009 | ns | 1.82 | - | 1.82 | - | 1.82 | - | 1.82 | AS |
| Galetto et al. (2017) | Wheat[2] | 2014 | ns | 3.85 | - | 3.85 | - | 3.85 | - | 3.90 | AS |
| | | | | 0 | 58 | 115 | 173 | - | - | - | |
| Lourente et al. (2007) | Corn[2] | 2001/02 | ns | 5.87 | 5.87 | 5.87 | 5.87 | - | - | - | AS |
| Yano et al. (2005) | Wheat | 2003 | ns | 3.82 | 3.46 | - | - | - | - | - | AS |
| | | | | 0 | 40 | 40 | 40 | 40 | 40 | 40 | |
| Broch et al. (2011) | Soybean[3] | 2003-05 | * | 2.88 | 3.15 | 3.38 | 3.18 | 2.97 | 3.25 | 3.37 | Factor |
| | | | | 0 | 13 | 25 | 29 | 38 | 57 | 86 | |
| Lange et al. (2014) | Corn | 2008/09 | ns | 6.39 | 6.41 | 6.41 | 6.38 | 6.41 | 6.38 | 6.38 | AS |
| | | | | 0 | 69 | 103 | 137 | 171 | - | - | |
| Barbosa Filho et al. (2005) | Bean | 1999 | ns | 3.75 | 3.65 | 3.65 | 3.65 | 3.65 | - | - | AS |
| Barbosa Filho et al. (2005) | Bean | 2000 | ns | 2.69 | 2.58 | 2.58 | 2.58 | 2.58 | - | - | AS |
| Barbosa Filho et al. (2005) | Bean | 2001 | ns | 2.81 | 2.71 | 2.71 | 2.71 | 2.71 | - | - | AS |

[1] Effects observed in the original studies, with * = significant (p<0.05) and ns = not significant. [2] Data extracted directly from figures. [3] Mean values for three crop harvests. S$^0$ = elemental sulfur; SSP = single superphosphate; AS = Ammonium sulfate; Factor = more than one S-source was tested.

(Lock et al., 2017). Those results yielding P-values less than 0.05 in randomized tests were assumed to be significant. The main factors governing crop responses to S fertilization were identified by using the conditional inference regression trees procedure in the Jmp® v. 13 (SAS, Inc., Cary, NC, USA). This statistical procedure is indicated for datasets obtained from literature searches, such as systematic reviews or meta-analyses retrieving studies which neither used all factors in the original trial - and in a randomized manner - nor replicated all levels within experiments (Mourtzinis et al., 2018). According to Tittonel et al. (2008), the conditional inference regression tree method makes no assumptions about the statistical distribution of data, and it is robust to outliers and multicollinearity of data.

We assessed the importance of categorical variables (crop type, climate, state of the experimental site, soil type, average crop yield) and continuous variables (soil available $SO_4^{2-}$-S content, OM, clay content and pH, and S rate) together, as factors in the partition, and crop response to S fertilization (viz., a positive response or no statistical difference) as a response variable. The partition was based on tests of the global null hypothesis of independence (p<0.05) between the factor variable and a response variable. When the hypothesis was rejected, the algorithm identified the factor most closely associated to the response variable (Mourtzinis et al., 2018). To ensure adequate power at all steps

of the partition and to avoid particularizing the results, each intermediate node had to account for at least 10 crop harvests (>20 % of all), and all terminal nodes had to contain at least 5 (>10 % of all).

## RESULTS AND DISCUSSION

### Characterization of studies on S fertilization

Studies evaluating the effect of S rates applied to grain crops grown on NT soils in Brazil are relatively recent; they began in 2005, and the results of most (57 %) were reported from 2013 to 2017 (Table 1). The studies focused on Central-Southern Brazil (Figure 1a), where the largest numbers of crop harvests evaluated (83 %) were those for the states of Paraná (31 %), Rio Grande do Sul (26 %), Goiás (14 %), and Mato Grosso do Sul (12 %) (Figure 1b). The crop harvests corresponded to tropical zones in 43 % of cases and subtropical zones in 57 % (Figure 1a). Soybean, corn, and wheat combined accounted for 78 % of the crops, reflecting their economic importance in Brazil (Figure 1c). The average yield for the crop harvests was quite high: 33 % had high yield (Figure 1d). Most of the studies involved Oxisols (83 %), followed by Ultisols (14 %), and Alfisols (3 %) (Figure 1e) which corresponds to *Latossolos*, *Argissolos*, and *Nitossolos* according to Brazilian Soil Classification System, respectively (Santos et al., 2013). Oxisol is the predominant soil order in Brazilian agriculture (Dalla Nora and Amado, 2013). As can be seen from figure 2a, the soils in 94 % of the studies had low or medium OM content (<5 %; CQFS-RS/SC, 2016). The soils in 77 % of the studies were clayey (>35 % clay; figure 2b), and in 75 % of the studies, the available $SO_4^{2-}$-S content was lower than 10 mg dm$^{-3}$ (Figure 2c). Finally, soil pH in the primary studies exhibited little variability, 50 % of soils had pH from 5.2 to 5.8 (Figure 2d).

### Positive responses of crop yield to S fertilization

The available $SO_4^{2-}$-S content was the only soil property among those studied that influenced crop response to S fertilization (Figure 3a). The critical level of soil available $SO_4^{2-}$-S [viz., 5 and 10 mg dm$^{-3}$ for low- and high S-demanding crops, respectively (CQFS-RS/SC, 2016)] provided a reliable criterion for defining crop yield response to S fertilization. Thus,
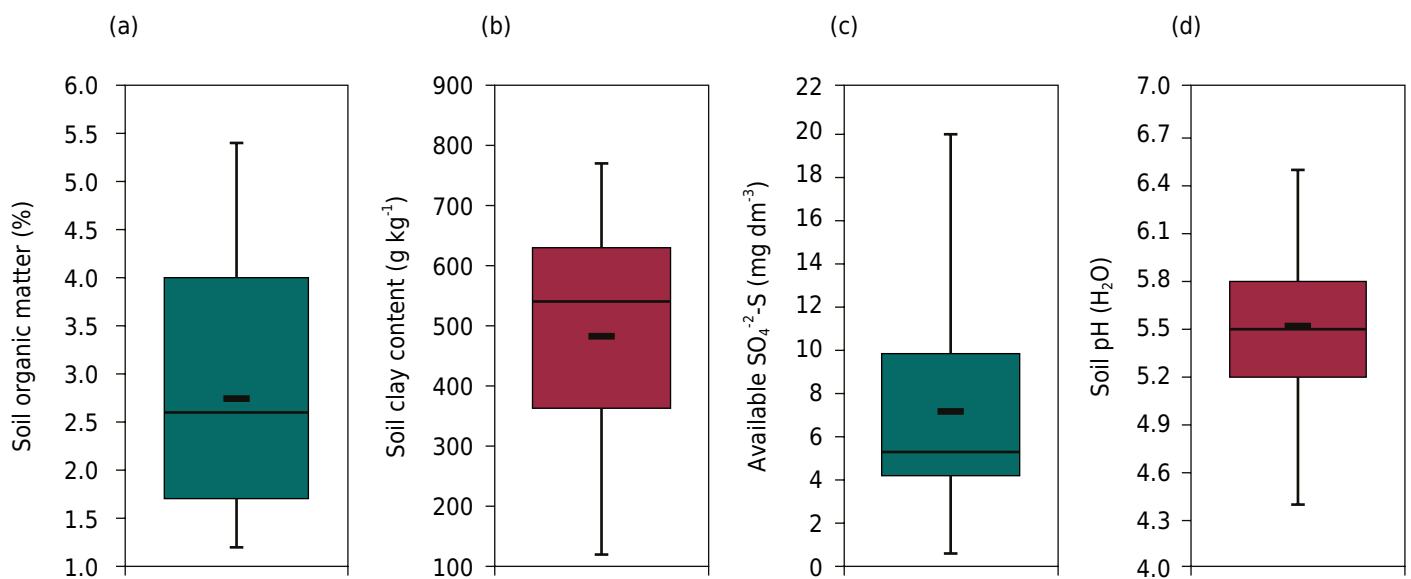


**Figure 2.** Descriptive statistical parameters of soil organic matter (a), soil clay content (b), available $SO_4^{-2}$-S content (mg dm$^{-3}$) (c), and soil pH(H$_2$O) values (d) in the studies that evaluated the effects of sulfur fertilization on crop yield in no-till soils in Brazil. The central rectangle of the box-plots spans the first to the third input quartile. The extended line inside the rectangle is the median, the dash is the mean, and the vertical lines above and below the box extend to the minimum and maximum values, respectively.

no positive response was observed in soils where available $SO_4^{2-}$-S exceeded the critical level in any crop harvest. In S-poor soils, however, positive responses were observed in 50 % of the crop harvests. This result shows that existing recommendations established for CT cropping systems are applicable under NT conditions, especially when the soil available $SO_4^{2-}$-S content exceeds the critical level. However, if available $SO_4^{2-}$-S is below the critical level, the recommendations should be refined in terms of additional factors for decision making, such as soil properties (pH, clay, and OM contents), climate, and crop characteristics, to make them more reliable.

As can be seen from figures 3b and 3c, the response to S fertilization was independent of the soil OM and clay contents. Clayey soils with oxidic mineralogy adsorb sulfate more readily, thereby reducing leaching of the anion to subsurface layers (Alvarez V et al., 2007; Ercoli et al., 2011). However, these soil conditions may also result in high stabilization of OM through organomineral interactions and thus detract from microbial decomposition and S mineralization of OM (Cotrufo et al., 2013), which is the main source of available $SO_4^{2-}$-S for plants (Alvarez V et al., 2007; Tiecher et al., 2013). In contrast, most low OM soils have lower physical, chemical, and microbiological quality (Mendes et al., 2018), which may lead to decreased crop grain yields and, consequently, decreased S requirements (Alvarez V et al., 2007). Another factor to be considered is atmospheric deposition of S, which increases with nearness to the sea or an industrialized city (Tiecher et al., 2013; Vieira-Filho et al., 2015). This deposition can thus have a confounding effect of texture and soil OM content on crop response to S fertilization. In addition, the fact that crop
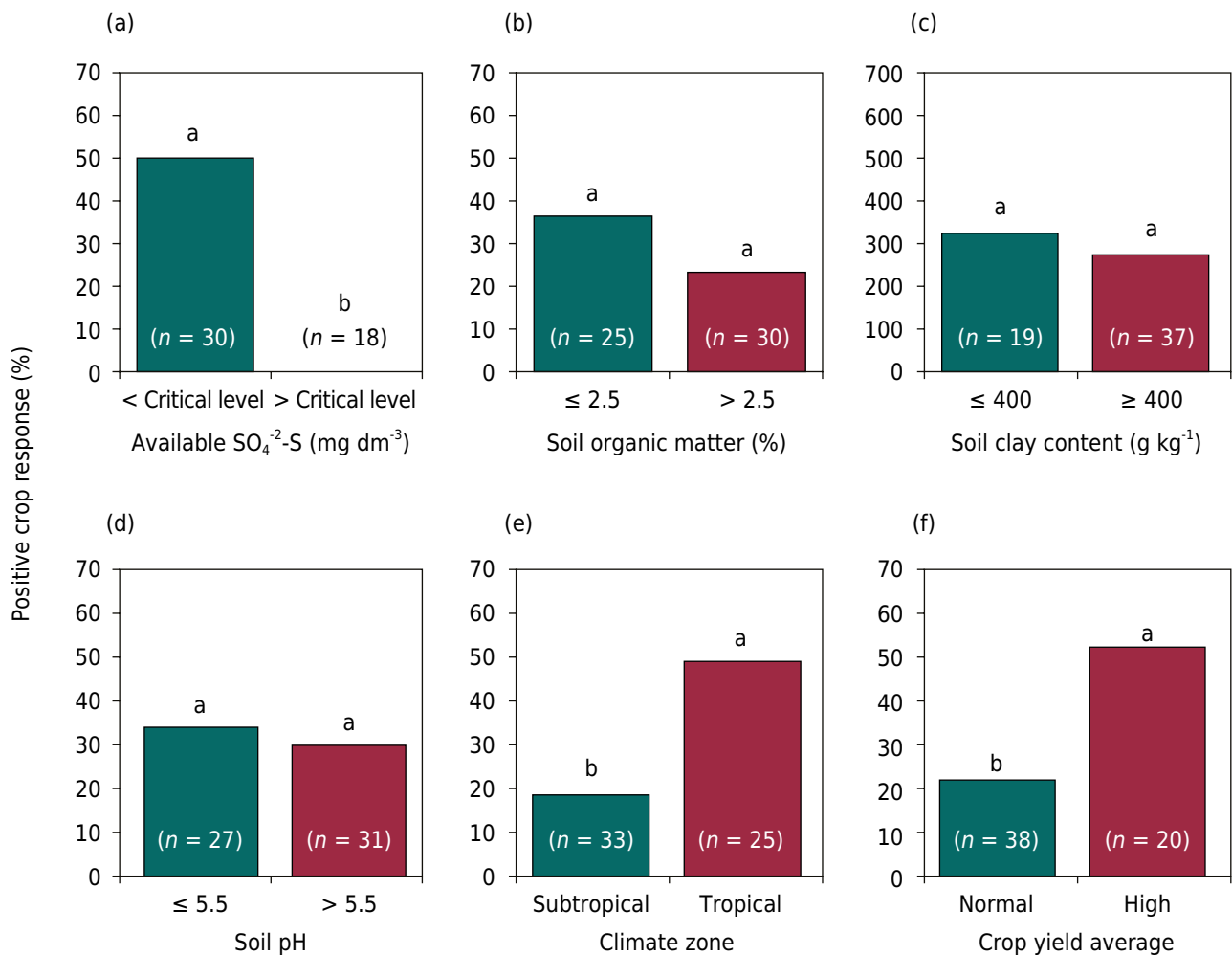


**Figure 3.** Relative frequency of positive crop response to sulfur fertilization in no-till soils with different available $SO_4$-S contents (a), organic matter (b), clay content (c), pH values (d), climate zone (e), and crop yield average (f). The number of crop harvests in each subgroup is shown in parentheses.

response to S fertilization was not related to either soil OM or clay content may have resulted from differences in recent S management history among fields. Eriksen et al. (1995) studied various types of Danish soils and found OM mineralization - and hence $SO_4^{2-}$-S availability to plants - not to be correlated with soil OM content but correlated with microbiological activity. Therefore, developing straightforward, inexpensive tools for quantifying biological activity in soil could be very useful to improve existing S fertilization recommendations for NT soils.

Soil pH may influence crop response to S fertilization. In fact, a high pH facilitates $SO_4^{2-}$ leaching to subsurface layers (Rheinheimer et al., 2005; Sutar et al., 2017). No such effect was observed here (Figure 3d), however, possibly because more than 75 % of the soils had pH <5.8 (Figure 2c).

Based on the results of this systematic review, crops grown on tropical soils are more likely to be S responsive than are those on subtropical soils in Brazil (48 % vs 18 %; Figure 3e), which is consistent with previously reported findings (Rein and Sousa, 2004; Alvarez V et al., 2007). This result can be ascribed to a number of factors, including low natural soil fertility and high soil weathering and acidity (Fageria and Nascente, 2014). The results also suggest that crops with increased yields are more likely to be responsive to S fertilization (Figure 3f). Since high-yield crops typically extract large amounts of S from the soil [usually 0.1-0.5 % of dry matter (Alvarez V et al., 2007; CQFS-RS/SC, 2016; Sutar et al., 2017)], S requirements can be expected to increase with increasing yield (Rheinheimer et al., 2005; Salvagiotti et al., 2017). In Brazil, soybean yields have risen by 30 % and corn yields by 85 % over the last 10 years (2006-2016) compared to the 1990s (1990-2000) (Conab, 2018); therefore, the probability of a positive response to S fertilization has likewise increased.

Only 18 (31 %) of the 58 crop harvests examined exhibited statistically significant positive responses to S fertilization (Figure 4a). Corn and bean were the most responsive crops, with increased yields in 46 % ($n = 13$) and 50 % ($n = 6$) of the crop harvests, respectively. Soybean responded in only 35 % ($n = 20$) of the crop harvests. In contrast, wheat only exhibited increased yields in one of 13 crop harvests and canola in one of 6. The increased responsiveness of corn and soybean relative to wheat and canola was probably associated with improved genetic potential of new commercial hybrids and varieties of corn and soybean, as well as with more intensive use of new technologies (Mendes et al., 2018) that facilitate S removal through grain harvest. With high S-demanding crops, soil available $SO_4^{2-}$-S and S inputs from atmospheric deposition may not suffice to fulfill crop nutritional requirements and replenish $SO_4^{2-}$-S losses (Rheinheimer et al., 2005; Alvarez V et al., 2007; Ercoli et al., 2012).

Within positive crop responses to S fertilization, corn exhibited the greatest yield increase (6-36 %, average = 19 %), followed by soybean (9-27 %, average = 16 %), and bean (9-15 %, average = 12 %) (Figure 4b). In the average of all crops with positive response to S fertilization, grain yield increased by 16 %. In Argentina, Salvagiotti et al. (2017) reported a positive response of corn to S fertilization under NT in 8 out of 17 years and an average grain yield increase of 13 %. In areas under CT of sub-Saharan Africa, a meta-analysis by Kihara et al. (2017) revealed that 76 % of the crops responded positively to S fertilization, with an average increase of 35 % in grain yield. These results testify to the importance of properly managing S fertilization in order to increase crop grain yields with a view to meeting growing worldwide demand for food (OECD/FAO, 2015) and to increasing crop profitability.

**Influence of S application rate on crop yield**

Based on the calibration curve for the crop harvests where S fertilization led to a statistically significant increase in grain yield (p<0.05) in the primary studies, the S application rate of maximum economic efficiency (MEE) was calculated to be 26 kg ha$^{-1}$.

This rate, which sufficed to obtain 95 % of the maximum yield for all crops (Figure 5a), is identical to that found by Carmona et al. (2009) in 12 experiments with CT managed flooded rice in the state of Rio Grande do Sul. In addition, it is similar to the officially recommended rate for the tropical Cerrado region (Rein and Sousa 2004), the state of São Paulo (Raij et al., 1997), and subtropical agricultural areas in southern Brazil (CQFS-RS/SC, 2016): (20 kg ha$^{-1}$ S). Sulfur rates recommended for the state of Paraná range from 20 to 40 kg ha$^{-1}$, depending on crop type (Pauletti and Motta, 2017). However, these values differ greatly from those recommended by Sfredo et al. (2003) for soybean: 70-110 kg ha$^{-1}$ S, depending on the soil available $SO_4^{2-}$-S content. Salvagiotti et al. (2017) found the MEE rate of S for corn grown on NT soils in Argentina to be 10 kg ha$^{-1}$. Also, in two lysimetric experiments conducted in central Italy, Ercoli et al. (2012) found S uptake by two durum wheat cultivars to be 32 kg ha$^{-1}$; however, only 25 % (8 kg ha$^{-1}$) was present in the grain. Sulfur leaching from this soil, which contained <5 % clay, was 35 kg ha$^{-1}$ and S atmospheric deposition was 14.5 kg ha$^{-1}$. Therefore, replenishing the S lost and S exported to grains required an input of 28.5 kg ha$^{-1}$ S, which is very similar to that found in this review of Brazilian studies.

In fact, as shown here and as is apparent from existing recommendations for Brazilian soils (Raij et al., 1997; Rein and Sousa 2004; CQFS-RS/SC, 2016; Pauletti and Motta, 2017), even S-deficient soils usually require only low rates of S fertilization. Ercoli et al. (2012) found that $SO_4^{2-}$-S availability in the soil solution changes significantly according to rainfall and OM mineralization throughout the crop cycle. As a result, a low S rate often suffices to fulfill the nutritional requirements of plants (Salvagiotti et al., 2017). Fertilizing soil with S is intended to sustain available $SO_4^{2-}$-S contents, which can amount to more than 70 % of the total S uptake by plants, and also to replenish soil S removed by grain harvest (Degryse et al., 2018).

### Influence of S source on crop response

The small amount of S (~ 26 kg ha$^{-1}$) to be added in order to supplement that supplied by the soil to meet the nutritional requirements of crops can be provided by various fertilizers. The most common S sources used in Brazil are ammonium sulfate [$(NH_4)_2SO_4$,
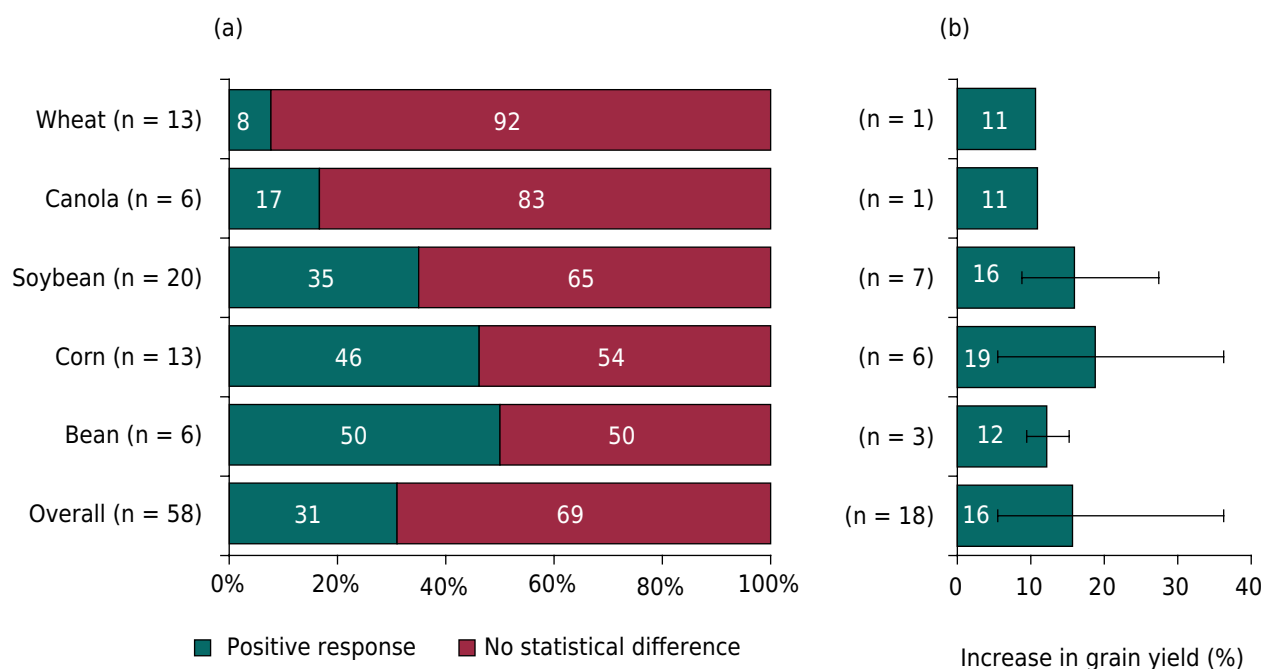


**Figure 4.** Relative frequency of crop response to sulfur fertilization in no-till soils in Brazil (a) and average increase in grain yield (%) for the crops with positive response (b). Error bars represent the ranges of crop responses.
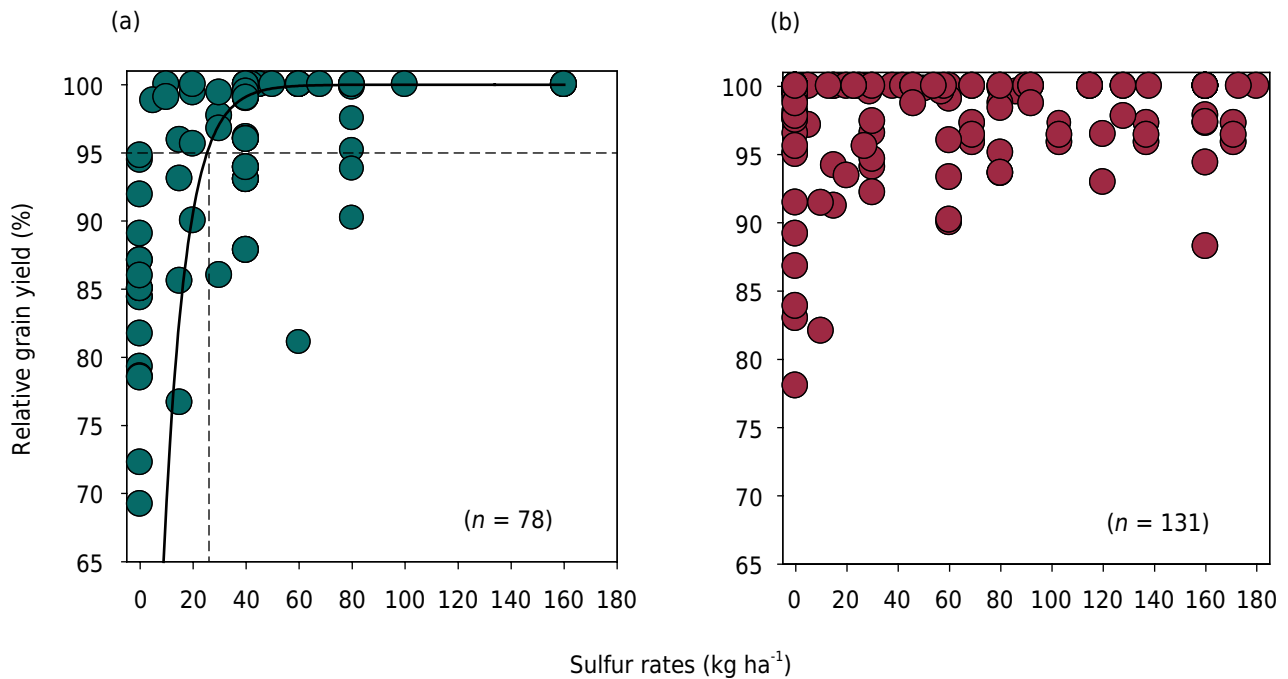
(a)

(b)



**Figure 5.** Relative grain yields of different crops and crop harvests with positive response (a) and with no response (b) to sulfur fertilization in no-till soils in Brazil. The graphs were elaborated from data presented in table 1. The number of observations in each subgroup is shown in parentheses.

22-24 % S], single superphosphate (10-12 % S), potassium sulfate ($K_2SO_4$, 15-17 % S), calcium sulfate (gypsum, $CaSO_4$, 13 % S), and elemental S (95 % S). All these sources, except elemental S, contain S as $SO_4^{2-}$, which is readily taken up by plants immediately after application (Horowitz and Meurer, 2006). Elemental S must be oxidized to $SO_4^{2-}$ before it can be taken up. Elemental S is oxidized mainly by autotrophic and heterotrophic microorganisms at a rate that depends on factors such as fertilizer grain size, soil aeration, temperature, moisture, OM and nutrient contents, soil acidity, and microbial biomass (Horowitz and Meurer, 2006, 2007). Horowitz and Meurer (2007) evaluated elemental S oxidation in 42 soil samples from different Brazilian states and concluded that all soils were able to oxidize elemental S, albeit at significantly different rates. Horowitz and Meurer (2006) found elemental S application to significantly increase $SO_4^{2-}$ availability to plants after 20 days.

The efficiency of the S sources cited above has been investigated in areas under NT in Brazil. Thus, Fiorini et al. (2016) found no differences in crop yield after application of elemental S and ammonium sulfate. In contrast, Broch et al. (2011) found that various S sources, including single superphosphate, gypsum, and granulated gypsum, increased soybean yield, but elemental S did not. However, Fano (2015) found elemental S to be more efficient than gypsum in increasing wheat yield. These conflicting results call for further, deeper investigation of the influence of S sources on crop response by determining whether sources containing S readily available for plants to take up (e.g., gypsum, single superphosphate) or those requiring prior oxidation in soil (e.g., elemental S) are more efficient (Broch et al., 2011; Degryse et al., 2018). As a slow-release fertilizer, elemental S allows increased S application rates to be used due to its marked residual effect and lower potential for short-term losses; both of these aspects increase efficient use of S, especially in high-rainfall environments and sandy soils (Degryse et al., 2018).

### Grain yield response to soil available $SO_4^{2-}$-S content

The critical levels of available $SO_4^{2-}$-S content for the surface layers (0.00-0.10 and 0.00-0.20 m) of Brazilian soils typically range from 3 to 10 mg $dm^{-3}$, as extracted by $Ca(PO_4)_2$ (Raij et al., 1997; Lopes et al., 2004; CQFS-RS/SC, 2016; Pauletti and Motta, 2017).

However, several studies have found no correlation between soil available $SO_4^{2-}$-S and crop grain yield (Rheinheimer et al., 2005; Osório Filho et al., 2007; Lucas et al., 2013) - not even at available $SO_4^{2-}$-S contents below these critical levels. This suggests that the available $SO_4^{2-}$-S content in the soil surface layer may not be an accurate predictor of crop response. In fact, such a content depends on various factors, including OM mineralization rate, atmospheric S deposition, plant uptake, rainfall, and soil texture (Ercoli et al., 2012; Blum et al., 2013; Tiecher et al., 2013; Sutar et al., 2017). As a result, the available $SO_4^{2-}$-S content changes during the crop cycle and it is difficult to match it to plant requirements (Ercoli et al., 2012). In addition, crop response to S fertilization follows a quadratic or exponential tendency in which, once the nutritional requirements of plants have been met, a further increase in soil available $SO_4^{2-}$-S results in no increase in yield (Lucas et al., 2013).

The soil available $SO_4^{2-}$-S content in the surface layer (48 crop harvests) and subsurface layer (34 crop harvests) was calibrated with crop grain yield. The critical levels for obtaining yields exceeding 95 % of the maximum possible value were 7.5 mg dm$^{-3}$ for the 0.00-0.20 m (Figure 6a) layer and 8.5 mg dm$^{-3}$ for the 0.20-0.40 m layer (Figure 6b). These critical levels are similar to that reported by Carmona et al. (2009) for the surface layer (0.00-0.20 m) of soil under flooded rice in the state of Rio Grande do Sul: 9.0 mg dm$^{-3}$. It is also in line with the critical level established by the Pauletti and Motta (2017) for the subsurface soil layer (0.20-0.40 m) of soils in Paraná, 9 mg dm$^{-3}$, and with the levels initially used in the discussion of this study [viz., 5 and 10 mg dm$^{-3}$ for crops with lower and higher requirements, respectively; CQFS-RS/SC (2016)]. Consistent with previous studies (Rheinheimer et al., 2005; Osório Filho et al., 2007), the results confirmed that it was unnecessary to classify crops as high S-demanding (e.g., soybean, beans, canola) and low S-demanding (e.g., wheat, corn) as previously done by CQFS-RS/SC (2016). In general, cereal crops have lower S contents in leaf tissue but higher demand in terms of grain yield potential, which results in their degree of S removal at harvest being similar to S removal in legume crops (Alvarez V et al., 2007; Sutar et al., 2017).

This systematic review of studies evaluating crop responses to S fertilization in NT soils shows that both the S rate recommendations and the critical levels used as
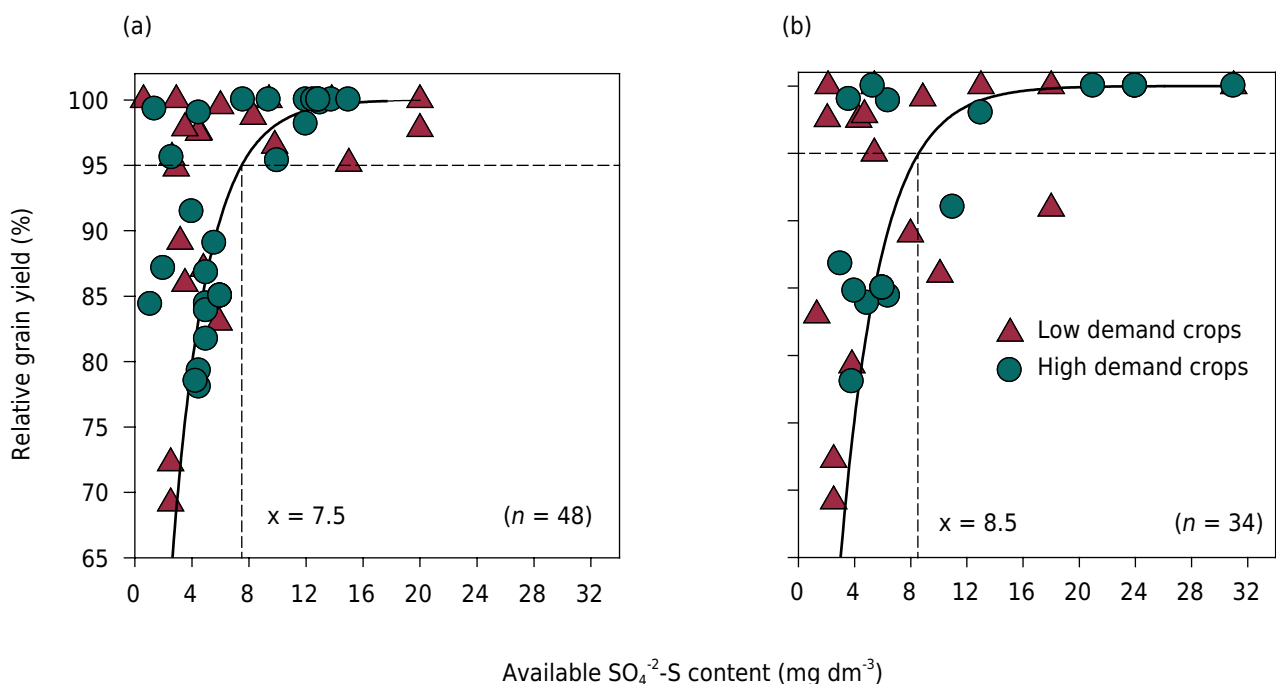


**Figure 6.** Relative grain yield of the crops as a function of soil S content in the surface layer (0.00-0.20 m) (a) and subsurface layer (0.20-0.40 m) (b) in no-till soils in Brazil. Low S demand crops included wheat and corn, and high S demand crops included soybean, canola, and bean. The number of crop harvests in each subgroup is shown in parentheses.

criteria for deciding whether to apply S fertilization are similar to those currently used in Brazil, which were established under CT conditions (Raij et al., 1997; Rein and Sousa, 2004; CQFS-RS/SC, 2016; Pauletti and Motta, 2017). These results rebut our hypothesis that crops grown under a NT system require higher S fertilizer rates than those established under a CT system. Probably, the greater physical and biological quality of soil found under NT increases $SO_4^{2-}$-S availability to plants, offsetting potential $SO_4^{2-}$-S leaching to subsurface layers induced by low acidity and higher nutrient content in the surface layer (Scherer, 2001), the greater S requirements of modern high-yield potential genotypes (Salvagiotti et al., 2017), and decreased atmospheric S deposition (Vieira-Filho et al., 2015). This was confirmed by Karlen et al. (2013), who found a higher available $SO_4^{2-}$-S content under long-term NT soil compared to CT soil, especially in the surface layer (0.00-0.05 m).

### Sulfur content of leaf tissue and grain yield

Our results showed no relationship between the S content of leaf tissue and the relative grain yield of five different crops spanning 31 crop harvests (Figure 7). Some authors found that S in leaf tissue increased with S application to soil; however, this effect resulted in no increase in grain yield (Rheinheimer et al., 2005; Frandoloso et al., 2010; Moda et al., 2013). Therefore, using leaf tissue analysis alone to guide S application requires caution because annual crops tend to take up nutrients in amounts exceeding their basic nutritional requirements (luxury consumption) (Ercoli et al., 2011). In addition, nutrient contents may vary widely throughout stages in the crop cycle and hinder accurate calibration of S recommendations. The results of this systematic review confirm the findings of Crusciol et al. (2006) for bean in Brazil, and those of Divito et al. (2015) for soybean at 15 different sites in Argentina. The latter authors found no relationship between leaf tissue S content and relative soybean yields, and they concluded that the N:S and P:S ratios in soybean leaves were more effective for guiding S management. In any case, leaf tissue analysis may be an effective tool for monitoring the need for S fertilization in soils with available $SO_4^{2-}$-S content below the critical level.

### Conditional inference tree for crop response to S fertilization in Brazilian no-till soils

Based on conditional inference tree analysis, four factors of variation (*viz.,* soil available $SO_4^{2-}$-S content, climate, crop type, and average crop yield) explained 63 % of crop responses to S fertilization (Figure 8). Soil available $SO_4^{2-}$-S content was the main factor influencing crop response. The critical content of soil available $SO_4^{2-}$-S for the 0.00-0.20 m layer was 7.6 mg $dm^{-3}$, which is similar to that calculated from the calibration curve (7.5 mg $dm^{-3}$; Figure 6a). Therefore, no positive response occurred with soil S ≥7.6 mg $dm^{-3}$. In contrast, the probability of a positive response to S fertilization with a soil available $SO_4^{2-}$-S content below 7.6 mg $dm^{-3}$ was 50 %. This result confirms the effectiveness of existing S fertilization recommendations for Brazilian no-till soils, which rely on soil S content as the sole decision-making criterion (Lopes et al., 2004; Rein and Sousa, 2004; CQFS-RS/SC, 2016). However, these recommendations could be refined for S-deficient soils (i.e., soils with an available $SO_4^{2-}$-S content below the critical level). The use of additional criteria in S-deficient soils might improve the efficiency of S fertilization management.

In fact, based on our results, climate was a key factor for crop response to S fertilization in S-deficient soils (Figure 8). The probability of a positive crop response was much higher in tropical soils (92 % positive responses) than it was in subtropical soils (22 % positive responses). Tropical soils are generally highly weathered and thus have low OM content, especially when not managed properly as regards crop rotation and biomass input (Fageria and Nascente, 2014). Because OM is the main source of S in soil, a low OM content raises the likelihood of S deficiency (Alvarez V et al., 2007).
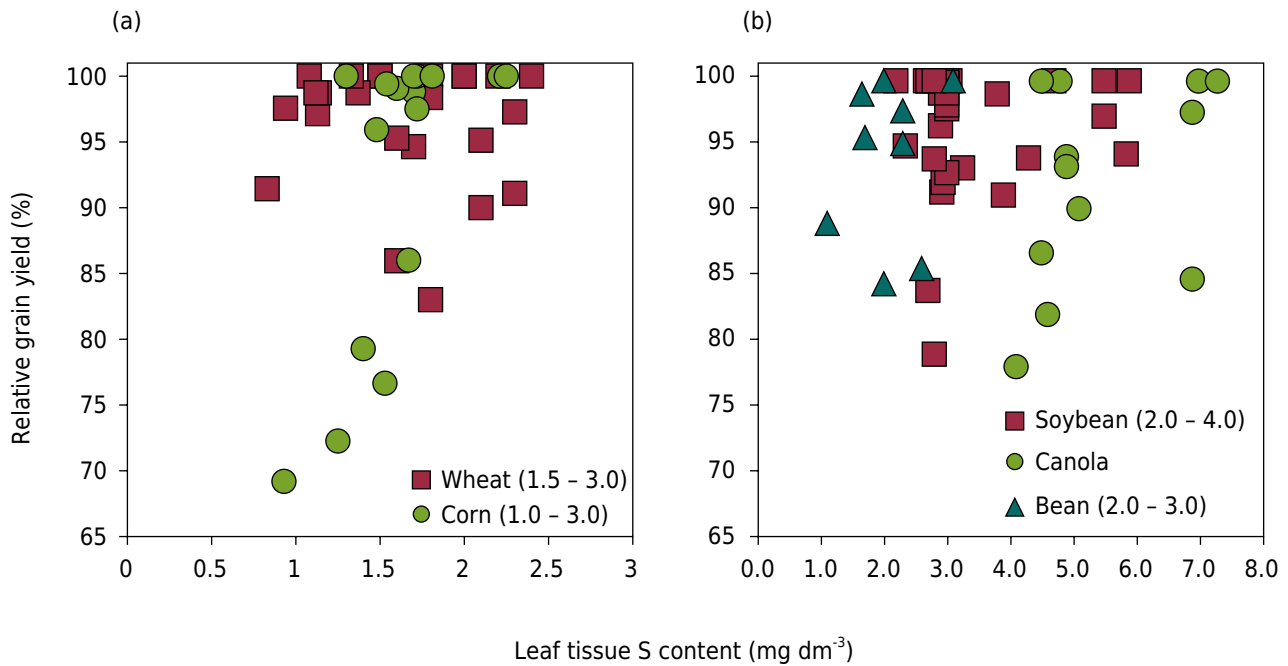
**Figure 7.** Relationship between leaf tissue S content and relative crop grain yield of wheat and corn (a), and soybean, canola, and bean (b). The range of S content suitable for each crop is shown in parentheses (CQFS-RS/SC, 2004; Alvarez V et al., 2007; Pauletti and Motta, 2017). For canola, there was no range of interpretation for S contents in leaf tissue.

Highly yielding crops grown on tropical soils with available $SO_4^{2-}$-S contents below the critical level responded positively to S fertilization in all crop harvests ($n = 7$). High-yield crops consequently need a greater amount of S available to be taken up for a positive crop response to S fertilization (Salvagiotti et al., 2017). The probability of a positive response in subtropical soils was low (22 %), even if the available $SO_4^{2-}$-S content was below the critical level - and this probability was as low as 9 % for crops such as soybean, canola, and wheat. This result is very important because soybean accounted for approximately 75 % of the area planted to grain crops in the 2017/18 summer season in this region (Conab et al., 2018).

## Suggestions for future research into S fertilization in Brazil

Studies on S fertilization in Brazil have primarily focused on Oxisols in the states of Paraná, Rio Grande do Sul, Goiás, and Mato Grosso do Sul. Future studies aiming at better understanding of crop response to S fertilization should be conducted under different geographical conditions expanding across the Cerrado region. This is the largest grain-producing region in Brazil and comprises the largest agricultural boundary in the world; one that spans the states of Maranhão, Tocantins, Piauí, and Bahia, which has been called "MATOPIBA".

The effect of S sources should be further investigated in order to clarify some contrasting results (Broch et al., 2011; Fano, 2015; Fiorini et al., 2016). In addition, the potential of S fertilization for improving quality in grain crops such as wheat should be better explored, as well as the effect of splitting S applications to ensure better adjustment of soil $SO_4^{2-}$-S availability to plant requirements and reduce S losses by leaching (Ercoli et al., 2011; Fano, 2015). Mapping S inputs via atmospheric deposition could be very useful for calculating soil S balances and refining S fertilization recommendations, as well as for identifying specific regions with an increased likelihood of positive crop responses. Long-term studies of crop response to S fertilization under NT conditions are required for more sustainable S management in tropical and subtropical soils of Brazil and other regions in the world.
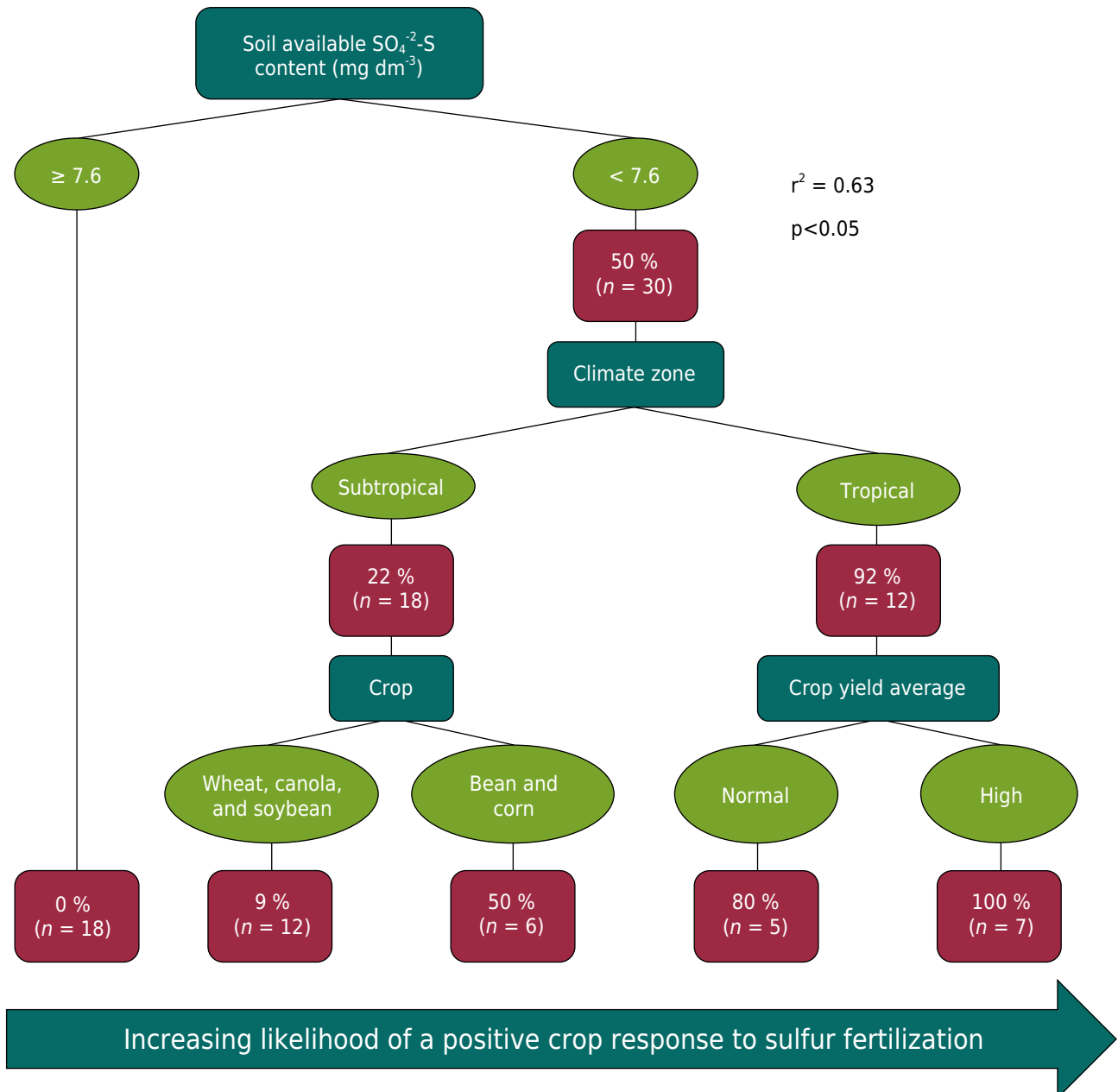
**Figure 8.** Conditional inference tree of the proportion of crop harvests with positive crop responses to sulfur fertilization in no-till soils in Brazil. The proportion number ranges from 0 to 100 %, where 0 % means that no crop harvest had a positive response to sulfur fertilization and 100 % means that all crop harvests had positive responses. The total number of crop harvests in each subgroup is shown in parentheses.

## CONCLUSIONS

Sulfur fertilization increased crop yield an average of 16 % in 31 % of the crop harvests studied in NT soils in Brazil. Bean, corn, and soybean were grain crops more responsive to S fertilization, and canola and wheat were less responsive. When a positive crop response was observed, 26 kg ha$^{-1}$ was the maximum economically efficient (MEE) rate of S (*i.e.,* the rate needed to obtain ≥95 % of the highest possible yield). The critical level of S in the soil surface (0.00-0.20 m) and subsurface layer (0.20-0.40 m) was 7.5 (n = 51) and 8.5 mg dm$^{-3}$ (n = 39), respectively.

The main factor governing crop response to S fertilization in NT soils in Brazil is the soil available $SO_4^{2-}$-S content, with 50 % (n = 30) of the crop harvests exhibiting increased yields when $SO_4^{2-}$-S contents were below the critical level (*i.e.,* 7.5 mg dm$^{-3}$ in the 0.00-0.20 m soil layer). In general, the official recommendations established for

CT soils also held for grain crops grown on NT soils. In fact, the critical levels of soil available $SO_4^{2-}$-S and their respective S fertilizer recommendations were consistent with the values found in this systematic review of only NT trials. However, existing recommendations may be improved by using additional criteria. Thus, positive crop responses in S-deficient soils occurred more often in the tropical zones (92 % of crop harvests) than under a subtropical climate (22 % of crop harvests). Finally, S fertilization should be prioritized in NT soils with available $SO_4^{2-}$-S contents that do not exceed 7.5 mg dm$^{-3}$ in the 0.00-0.20 m layer, especially in the tropical zones. In addition, regional fertilizer recommendation guidelines should consider crop type and yield expectation in order to facilitate more sustainable S management and increased crop yields in Brazil.

# REFERENCES

Alvarez V VH, Roscoe R, Kurihara CH, Pereira NF. Enxofre. In: Novais RF, Alvarez V VH, Barros NF, Fontes RLF, Cantarutti RB, Neves JCL, editores. Fertilidade do solo. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2007. p. 595-644.

Barbosa Filho MP, Fageria NK, Silva OF. Fontes, doses e parcelamento da adubação nitrogenada em cobertura para feijoeiro comum irrigado. Cienc Agrotec. 2005;29:69-76. https://doi.org/10.1590/S1413-70542005000100008

Bissani CA, Gianello CG, Tedesco MJ, Camargo FA. Fertilidade dos solos e manejo da adubação de culturas. Porto Alegre: Genesis; 2008.

Blum SC, Garbuio FJ, Joris HAW, Caires EF. Assessing available soil sulphur from phosphogypsum applications in a no-till cropping system. Expl Agric. 2014;50:516-32. https://doi.org/10.1017/S0014479714000015

Blum SC, Lehmann J, Solomon D, Caires EF, Alleoni LRF. Sulfur forms in organic substrates affecting S mineralization in soil. Geoderma. 2013;200-2011:156-64. https://doi.org/10.1016/j.geoderma.2013.02.003

Broch DL, Pavinato PS, Possentti JC, Martin TN, Del Quiqui EM. Produtividade da soja no cerrado influenciada pelas fontes de enxofre. Rev Cienc Agron. 2011;42:791-6. https://doi.org/10.1590/S1806-66902011000300027

Carmona FC, Conte O, Fraga TI, Barros T, Pulver E, Anghinoni I. Disponibilidade no solo, estado nutricional e recomendação de enxofre para o arroz irrigado. Rev Bras Cienc Solo. 2009;33:345-55. https://doi.org/10.1590/S0100-06832009000200012

Comissão de Química e Fertilidade do Solo - CQFS-RS/SC. Manual de calagem e adubação para os Estados do Rio Grande do Sul e de Santa Catarina. 11. ed. Porto Alegre: Sociedade Brasileira de Ciência do Solo - Núcleo Regional Sul; 2016.

Companhia Nacional de Abastecimento - Conab. Preço dos insumos agropecuários 2017 [internet]. Brasília, DF: Ministério da Agricultura, Pecuária e Abastecimento; 2018 [cited 2018 Fev 15]. Available from: http://consultaweb.conab.gov.br/consultas/consultaInsumo.do?method=acaoCarregarConsulta.

Cotrufo MF, Wallenstein MD, Boot CM, Denef K, Paul E. The microbial efficiency-matrix stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Glob Change Biol. 2013;19:988-95. https://doi.org/10.1111/gcb.12113

Crusciol CAC, Soratto RP, Silva LM, Lemos LB. Aplicação de enxofre em cobertura no feijoeiro em sistema de plantio direto. Bragantia. 2006;65:459-65. https://doi.org/10.1590/S0006-87052006000300012

Dalla Nora D, Amado TJC. Improvement in chemical attributes of Oxisol subsoil and crop yields under no-till. Agron J. 2013;105:1393-403. https://doi.org/10.2134/agronj2013.0031

Dalla Nora D, Amado TJC, Nicoloso RS, Gruhn EM. Modern high-yielding maize, wheat and soybean cultivars in response to gypsum and lime application on no-till Oxisol. Rev Bras Cienc Solo. 2017;41:e0160504. https://doi.org/10.1590/18069657rbcs20160504

Degryse F, Silva RC, Baird R, Beyrer T, Below T, McLaughlin MJ. Uptake of elemental or sulfate-S from fall- or spring-applied co-granulated fertilizer by corn - a stable isotope and modeling study. Field Crop Res. 2018;221:322-32. https://doi.org/10.1016/j.fcr.2017.07.015

Divito GA, Echeverría HE, Andradea FH, Sadras VO. Diagnosis of S deficiency in soybean crops: performance of S and N:S determinations in leaf, shoot and seed. Field Crop Res. 2015;180:167-75. https://doi.org/10.1016/j.fcr.2015.06.006

Ercoli L, Arduini I, Mariotti M, Lulli L, Masoni A. Management of sulphur fertiliser to improve durum wheat production and minimise S leaching. Eur J Agron. 2012;38:74-82. https://doi.org/10.1016/j.eja.2011.12.004

Ercoli L, Lulli L, Arduini I, Mariotti M, Masoni A. Durum wheat grain yield and quality as affected by S rate under Mediterranean conditions. Eur J Agron. 2011;35:63-70. https://doi.org/10.1016/j.eja.2011.03.007

Eriksen J, Mortensen JV, Nielsen JD, Nielsen NE. Sulphur mineralisation in five Danish soils as measured by plant uptake in a pot experiment. Agr Ecosyst Environ. 1995;56:43-51. https://doi.org/10.1016/0167-8809(95)00632-X

Fageria NK, Nascente AS. Management of soil acidity of South American soils for sustainable crop production. Adv Agron. 2014;128:221-75. https://doi.org/10.1016/B978-0-12-802139-2.00006-8

Fano A. Fontes de enxofre e manejo de nitrogênio na produtividade e qualidade industrial de trigo [dissertação]. Pato Branco: Universidade Tecnológica Federal do Paraná; 2015.

Federação Brasileira de Plantio Direto na Palha - Febrapdp. Área de sistema plantio direto. Foz do Iguaçu: Febrapdp/Conab; 2012 [cited 2017 Out 5]. Available from: http://febrapdp.org.br/download/PD_Brasil_2013.jpg.

Fiorini IVA, von Pinho RG, Pires LPM, Santos AO, Fiorini FVA, Cancellier LL, Resende EL. Avaliação de fontes de enxofre e das formas de micronutrientes revestindo o NPK na cultura do milho. Rev Bras Milho Sorgo. 2016;15:20-9. https://doi.org/10.18512/1980-6477/rbms.v15n1p20-29

Frandoloso JF, Lana MC, Fontaniva S, Czycza RV. Eficiência de adubos fosfatados associados ao enxofre elementar na cultura do milho. Rev Ceres. 2010;57:686-94. https://doi.org/10.1590/S0034-737X2010000500019

Galetto SL, Bini AR, Haliski A, Scharr DA, Borszowskei PR, Caires EF. Nitrogen fertilization in top dressing for wheat crop in succession to soybean under a no-till system. Bragantia. 2017;76:282-91. https://doi.org/10.1590/1678-4499.095

Gelain E, Rosa Junior EJ, Mercante FM, Fortes DG, de Souza FR, Rosa YBCJ. Fixação biológica de nitrogênio e teores foliares de nutrientes na soja em função de doses de molibdênio e gesso agrícola. Cienc Agrotec. 2011;35:259-69. https://doi.org/10.1590/S1413-70542011000200005

Horowitz N, Meurer EJ. Relação entre atributos de solos e oxidação de enxofre elementar em quarenta e duas amostras de solos do Brasil. Rev Bras Cienc Solo. 2007;31:455-63. https://doi.org/10.1590/S0100-06832007000300005

Horowitz N, Meurer EJ. Oxidação do enxofre elementar em solos tropicais. Cienc Rural. 2006;36:822-8. https://doi.org/10.1590/S0103-84782006000300015

Karlen DL, Cambardella CA, Kovar JL, Colvin TS. Soil quality response to long-term tillage and crop rotation practices. Soil Till Res. 2013;133:54-64. https://doi.org/10.1016/j.still.2013.05.013

Kaefer JE, Guimarães VF, Richart A, Tomm GO, Müller AL. Produtividade de grãos e componentes de produção da canola de acordo com fontes e doses de nitrogênio. Pesq Agropec Bras. 2014;49:273-80. https://doi.org/10.1590/S0100-204X2014000400005

Kihara J, Sileshi GW, Nziguheba G, Kinyua M, Zingore S, Sommer R. Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. Agron Sustain Dev. 2017;37:25. https://doi.org/10.1007/s13593-017-0431-0

Lange A, Caione G, Schoninger EL, Silva RG. Produtividade de milho safrinha em consórcio com capim-marandu em função de fontes e doses de nitrogênio em cobertura. Rev Bras Milho Sorgo. 2014;13:35-47. https://doi.org/10.18512/1980-6477/rbms.v13n1p35-47

Lock RH, Lock PF, Morgan KL, Lock EF, Lock DF. Statistics: unlocking the power of data. 2nd ed. Nova Jersey: Wiley; 2017.

Lopes AS, Wiethölter S, Guilherme LRG, Silva CA. Sistema plantio direto: Bases para o manejo da fertilidade do solo. São Paulo: Associação Nacional para Difusão de Adubos; 2004.

Lopes LO, Moura MCS, Matias SSR, Lopes RS, Teixeira MPR. Effect of sources and doses of sulfate on soybean crop. Pesq Agropec Trop. 2017;47:296-302. https://doi.org/10.1590/1983-40632016v4745394

Lourente ERP, Ontocelli R, Souza LCF, Gonçalves MC, Marchetti ME, Rodrigues ET. Culturas antecessoras, doses e fontes de nitrogênio nos componentes de produção do milho. Acta Sci Agron. 2007;29:55-61. https://doi.org/10.4025/actasciagron.v29i1.66

Lucas FT, Coutinho ELM, Paes JMV, Barbosa JC. Yield and quality of canola grains due to nitrogen and sulfur fertilization. Semin-Cienc Agrar. 2013;34:3205-18. https://doi.org/10.5433/1679-0359.2013v34n6Supl1p3205

Marchesan E, Tonetto F, Teló GM, Coelho LL, Aramburu BB, Trivisiol VS. Soil management and application of agricultural gypsum in a Planosol for soybean cultivation. Cienc Rural. 2017;47:e20161102. https://doi.org/10.1590/0103-8478cr20161102

Megda MM, Buzetti S, Andreotti M, Teixeira Filho MMC, Vieira MX. Resposta de cultivares de trigo ao nitrogênio em relação às fontes e épocas de aplicação sob plantio direto e irrigação por aspersão. Cienc Agrotec. 2009;33:1055-60. https://doi.org/10.1590/S1413-70542009000400016

Mendes IC, Tormena CA, Cherubin MR, Karlen DL. Soil health assessment and maintenance in Central and South-Central Brazil. In: Don R, editor. Managing soil health for sustainable agriculture: monitoring and management. 2nd ed. Cambridge: Burleigh Dodds Science Publishing Limited; 2018. vol. 2. p. 360-75.

Mendes MC, Walter ALB, Possato Junior O, Rizzardi DA, Schlosser J, Szeuczuk K. Dose de nitrogênio associado a enxofre elementar em cobertura na cultura do milho em plantio direto. Rev Bras Milho Sorgo. 2014;13:96-106. https://doi.org/10.18512/1980-6477/rbms.v13n1p96-106

Miranda LN, Miranda JCC. Adubação de enxofre para a cultura do milho sob plantio convencional e direto em solo de cerrado. Planaltina: Embrapa Cerrado; 2008. (Comunicado Técnico, 143).

Moda LR, Borges BMMN, Flores RA, Santos CLR, Prado RM, Sousa JI. Gessagem na cultura da soja no sistema de plantio direto com e sem adubação potássica. Agro@mbiente On-line. 2013;7:129-35. https://doi.org/10.18227/1982-8470ragro.v7i2.948

Mourtzinis S, Kaur G, Orlowski JM, Shapiro CA, Lee CD, Wortmann C, Holshouser D, Nafziger ED, Kandel H, Niekamp J, Ross WJ, Lofton J, Vonk J, Roozeboom KL, Thelen KD, Lindsey LE, Staton M, Naeve SL, Casteel SN, Wiebold WJ, Conley SP. Soybean response to nitrogen application across the United States: a synthesis-analysis. Field Crop Res. 2018;215:74-82. https://doi.org/10.1016/j.fcr.2017.09.035

Nascente AS, Stone LF, Melo LC. Common bean grain yield as affected by sulfur fertilization and cultivars. Rev Ceres. 2017;64:548-52. https://doi.org/10.1590/0034-737X201764050013

Neis L, Paulino HB, Souza ED, Reis EF, Pinto FA. Gesso agrícola e rendimento de grãos de soja na região do sudoeste de Goiás. Rev Bras Cienc Solo. 2010;34:409-16. https://doi.org/10.1590/S0100-06832010000200014

Organisation for Economic Co-operation and Development/Food and Agriculture Organization of the United Nations - OECD/FAO. OECD-FAO Agricultural Outlook 2015-2024. Paris: OECD Publishing; 2015.

Osório Filho BD, Rheinheimer DS, Silva LS, Kaminski J, Dias GF. Deposição do enxofre atmosférico no solo pelas precipitações pluviais e respostas de culturas à adubação sulfatada em sistema plantio direto. Cienc Rural. 2007;37:712-9. https://doi.org/10.1590/S0103-84782007000300017

Pauletti V, Motta ACV. Manual de adubação e calagem para o estado do Paraná. Curitiba: Sociedade Brasileira de Ciência do Solo/Núcleo Estadual Paraná; 2017.

Pereira CS, Freitas AA, Chapla MV, Lange A. Doses de potássio com a presença de enxofre na cultura da soja. Gl Sci Technol. 2016;9:22-32.

Prando AM, Zucareli C, Fronza V, Oliveira FA, Oliveira Júnior A. Características produtivas do trigo em função de fontes e doses de nitrogênio. Pesq Agropec Trop. 2013;43:34-41. https://doi.org/10.1590/S1983-40632013000100009

Primo JP, Silva CAT, Fernandes FCS. Efeito da adubação com enxofre na cultura da soja. Cultivando o Saber. 2012;5:74-80.

Raij Bvan, Cantarella H, Quaggio JA, Furlani AMC. Recomendações de adubação e calagem para o Estado de São Paulo. 2. ed. rev. atual. Campinas: Instituto Agronômico/Fundag; 1997. (Boletim Técnico, 100).

Rampim L, Borsoi A, Dal Molin PV, Sarto MVM, Rosset JS, Lana MC, Lima PR, Guimarães VF, Ohland T, Klein J. Foliar tissue, grain yield and economic return by surface application of gypsum and different number of soybean plants in precision seed drill. Afr J Agric Res. 2015;10:1636-46. https://doi.org/10.5897/AJAR2014.8958

Rampim L, Lana MC, Frandoloso JF, Fontaniva S. Atributos químicos de solo e resposta do trigo e da soja ao gesso em sistema semeadura direta. Rev Bras Cienc Solo. 2011;35:1687-98. https://doi.org/10.1590/S0100-06832011000500023

Rein TA, Sousa DMG. Adubação com enxofre. In: Sousa DMG, Lobato E, editores. Cerrado: correção do solo e adubação. 2. ed. Planaltina: Embrapa Cerrados; 2004. p. 227-42

Rheinheimer DS, Alvarez JWR, Osorio Filho BD, Silva LS, Bortoluzzi EC. Resposta de culturas à aplicação de enxofre e a teores de sulfato num solo de textura arenosa sob plantio direto. Cienc Rural. 2005;35:562-9. https://doi.org/10.1590/S0103-84782005000300011

Salvagiotti F, Prystupa P, Ferraris G, Couretot L, Magnano L, Dignani D, BGutiérrez-Boemoem FHG. N:P:S stoichiometry in grains and physiological attributes associated with grain yield in maize as affected by phosphorus and sulfur nutrition. Field Crop Res. 2017;203:128-38. https://doi.org/10.1016/j.fcr.2016.12.019

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JÁ, Cunha TJF, Oliveira JB. Sistema brasileiro de classificação de solos. 3. ed. Brasília, DF: Embrapa; 2013.

Sávio FL, Silva GC, Teixeira IR, Mota JH, Borém A. Calagem e gessagem na nutrição e produção de soja em solo com pastagem degradada. Rev Agrotec. 2011;2:19-31. https://doi.org/10.12971/2179-5959.v02n01a02

Scherer HW. Sulphur in crop production - invited paper. Eur J Agron. 2001;14:81-111. https://doi.org/10.1016/S1161-0301(00)00082-4

Sfredo GJ, Klepker D, Ortiz FR, Oliveira Neto W. Enxofre: níveis críticos para a soja, nos solos do Brasil. In: Anais do XXIX Congresso Brasileiro de Ciência do Solo; julho 2003; Ribeirão Preto. Ribeirão Preto: Universidade Estadual Paulista; 2003.

Soares GF. Gesso e fósforo na sucessão soja/milho safrinha [dissertação]. Jataí: Universidade Federal de Goiás; 2016.

Souza ED, Costa SEVGA, Anghinoni I, Carneiro MAC, Martins AP, Bayer C. Soil quality indicators in a Rhodic Paleudult under long term tillage systems. Soil Till Res. 2014;139:28-36. https://doi.org/10.1016/j.still.2014.02.001

Sutar RK, Pujar AM, Kumar BNA, Hebsur NS. Sulphur nutrition in maize - a critical review. Int J Pure App Biosci. 2017;5:1582-96. https://doi.org/10.18782/2320-7051.6092

Tiecher T, Pias OHC, Bayer C, Martins AP, Denardin LGO, Anghinoni I. Crop response to gypsum application to subtropical soils under no-till in Brazil: a systematic review. Rev Bras Cienc Solo. 2018;42:e0170025. https://doi.org/10.1590/18069657rbcs20170025

Tiecher T, Santos DR, Alvarez JWR, Mallmann FJK, Piccin R, Brunetto G. Respostas de culturas à adubação sulfatada e deposição de enxofre atmosférico. Rev Ceres. 2013;60:420-7. https://doi.org/10.1590/S0034-737X2013000300016

Tittonel P, Shepherd KD, Vanlauwe B, Giller KE. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya - an application of classification and regression tree analysis. Agr Ecosyst Environ. 2008;123:137-50. https://doi.org/10.1016/j.agee.2007.05.005

Vieira-Filho MS, Lehmann C, Fornaro A. Influence of local sources and topography on air quality and rainwater composition in Cubatão and São Paulo, Brazil. Atmos Environ. 2015;101:200-8. https://doi.org/10.1016/j.atmosenv.2014.11.025

Vieira RCB, Fontoura SMV, Bayer C, Moraes RP, Carniel E. Potassium fertilization for long term no-till crop rotation in the central-southern region of Paraná, Brazil. Rev Bras Cienc Solo. 2016;40:e0150193. https://doi.org/10.1590/18069657rbcs20150193

Werner OV, Santos RF, Werner SS, Rosa HA, Secco D, Souza SNM, Nogueira CEC. Nitrogen and sulfur applied to the coverage of a canola crop in no-tillage system. Afr J Agric Res. 2013;8:1799-803. https://doi.org/10.5897/AJAR12.2131

Yano GT, Takahashi HW, Watanabe TS. Avaliação de fontes de nitrogênio e épocas de aplicação em cobertura para o cultivo do trigo. Semin-Cienc Agrar. 2005;26:141-8. https://doi.org/10.5433/1679-0359.2005v26n2p141

Zandoná RR, Beutler AN, Burg GM, Barreto CF, Schmidt MR. Gesso e calcário aumentam a produtividade e amenizam o efeito do déficit hídrico em milho e soja. Pesq Agropec Trop. 2015;45:128-37. https://doi.org/10.1590/1983-40632015v4530301