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SULFUR FERTILIZATION TECHNOLOGY IN THE ARGENTINE PAMPAS REGION: A REVIEW

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REVISIÓN

SUMMARY

Sulfur (S) deficiencies in grain crops have become increasingly frequent worldwide, including the Argentine Pampas region, located in South America. The objective of this work is to review recent research literature regarding S fertilization in the Argentine Pampas region, with emphasis on technological issues. The S fertilization in this region has grown sharply over recent years and, simultaneously, more scientific literature has been generated. A knowledge gap is recognized on field research studies related to elemental sulfur (ES) fertilization and its relative agronomic effectiveness in comparison to soluble S sources. By far, solid sulfate fertilizers are the most widespread S sources applied by farmers in the Pampas region. Nonetheless, application of liquid sources has increased over recent times. Overall, similar agronomic performance among sulfate sources has been reported. Additionally, similar effectiveness was documented between micronized ES and sulfate sources for different crops, with the exception of some site-specific conditions where effectiveness of sulfate sources may outperform ES. This review manuscript contributes to synthesize current knowledge regarding S fertilization technology and identify research needs in this matter.

Key words: sulfur, sulfur sources, elemental sulfur, sulfur fertilization.

TECNOLOGÍA DE FERTILIZACIÓN AZUFRADA EN LA REGIÓN PAMPEANA ARGENTINA: UNA REVISIÓN

RESUMEN

La frecuencia de ocurrencia de deficiencias de azufre (S) en cultivos de grano se incrementó a nivel mundial, incluyendo la Región Pampeana argentina, localizada en Sudamérica. El objetivo del trabajo es realizar una revisión de la literatura científica sobre fertilización azufrada en la Región Pampeana, con énfasis en aspectos tecnológicos. La adopción de la fertilización azufrada creció marcadamente en ésta región y simultáneamente aumentó la cantidad de publicaciones científicas en el tema. Sin embargo, existe una brecha de conocimiento sobre la fertilización con azufre elemental (AE) y su efectividad agronómica relativa a fuentes azufradas solubles. Los fertilizantes sulfatados sólidos son, con creces, las fuentes de S más utilizadas en la Región Pampeana aunque la aplicación de fuentes líquidas se incrementó en los últimos tiempos. En términos generales, se ha reportado similar efectividad agronómica entre fuentes sulfatadas. Asimismo, se ha observado similar efectividad agronómica entre el AE micronizado y fuentes sulfatadas en diferentes cultivos, con la excepción de condiciones sitio-específicas donde las fuentes sulfatadas pueden presentar una mejor performance. Esta revisión contribuye a sintetizar el conocimiento vigente sobre tecnología de fertilización azufrada y puede resultar de interés para establecer necesidades de investigación en este tema.

Palabras clave: azufre, fuentes azufradas, azufre elemental, fertilización azufrada.

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INTRODUCTION

Sulfur (S) plays a key role in plant growth. It is an essential amino acid component and participates in important biochemical and physiological processes, such as lipid and protein biosynthesis, photosynthesis, nitrogen (N) assimilation, and N biological fixation, among others (Mengel and Kirby, 2000; Rice, 2007). In oil-seeds, cereals and vegetables crops, S fertilization is also important for improving the quality of harvested products (Wang *et al.,* 2008). For many years, S received scarce attention as a plant nutrient around the world. This is principally due to the continuous S supply from different sources (*e.g.* rainfall, atmospheric depositions and some fertilizers sources with S traces) that have been prevented, to some extent, the occurrence of S deficiencies. Regarding S fertilizer sources, low or scant S is provided through the application of ''high analysis'' N, phosphate and potash fertilizers (Eriksen, 2005; Haneklaus *et al.,* 2007). The intensification of agriculture, as related to the increase in crop productivity per unit area and/or the number of crops within rotations, has led to an increase in S deficiencies due to the higher crop S demand at the cropping system level.

The awareness of S deficiencies in agro-ecosystems is increasing worldwide because of certain evidences of crop yield responses to S application in different regions around the world (*e.g.* USA, China, India, Brazil, Argentina, Australia, etc.). Recently, in a wide range of countries and farming conditions, research has shown significant increases in both crop yields and quality due to S fertilization (Til, 2010).

In South America, S deficiencies have been reported mainly in Brazil and Argentina (Prochnow and Blair, 2010; Stipp and Casarin, 2010; Torres Duggan and Rodríguez, 2011). In other countries such as Chile, Bolivia, Paraguay and Uruguay, S fertilization is not a generalized practice as can be verified by the low S fertilizer consumption in these countries (Torres Duggan and Rodríguez, 2011). Among this group of countries, Bolivia has an incipient fertilizer market and a low input agriculture system. Conversely, Chile can be considered as a mature fertilizer market (*i.e.* stabilized nutrient consumption). The main soil deficiency nutrients in the chilean cropping systems are N, P and K (Ponce and Torres Duggan, 2005). However, some S fertilization is carried out in southern regions, when grain crops and pastures are grown, mostly in Andisols (Alfaro *et al.,* 2006; Mora *et al.,* 2002). In other regions of the country, S fertilization is less frequent, may be associated with the widespread salt-affected soils, which have high soluble salt contents, including sulfate. However, in the northern regions, there is a significant use of S as amendment (elemental sulfur and gypsum) for ameliorating sodic soils (Mora *et al.,* 2002; Sierra *et al.,* 2007). In Paraguay, current S fertilization is uncommon, but because of the sharp intensification of the cropping systems observed over recent years, an increase in S deficiencies and yield response to S application may be expected for the near term. With regards to Uruguay, the main deficiency nutrients are N, P and potassium (K). However, yield responses to S application were reported in forage crops, under sandy soils (Casanova and Ferrando, 2010), while S fertilization in grain crops is not a common practice. This would be related to the high OM content of the soils, mostly Vertisols, and the short cropping history of the fields (the traditional farming systems are pasture and field crop rotations). However, this context has changed sharply over recent times due to the impressive expansion of soybean cultivation under no till systems, following a similar pattern to the argentine Pampas's (Melgar *et al.,* 2011). This scenario probably will lead to an increase in nutrient deficiencies, including S, as cropping systems become more intensives.

After N and phosphorous (P), S is the third limiting nutrient for crop growth in the argentine Pampas´s (García and Darwich, 2009). Furthermore, for the main four crops grown in Argentina (maize, soybean, wheat and sunflower), the ratio S applied/S removed by crops, has continuously grown since the 1990's. However, this ratio is currently close to

45% which can be interpreted as that only half of the S removed by the crops is being replenished by fertilization (Ciampitti *et al.,* 2009). This work aims to review the current scientific knowledge on S fertilization technology in the Pampas region of Argentina.

RESULTS AND DISCUSSION

Sulfur deficiencies and diagnosis overview in field crops

The Pampas region is the main agriculture production area in Argentina. Soils were initially very fertile and crop production (mainly cereal and oilseed crops) relied on this great natural soil fertility. Agriculture was based on crop nutrient removal from the soil for decades. This practice, although uncommon at more advance countries with similar soils (*e.g.* USA plains), was maintained for several reasons including decades of economically-unfavorable fertilizer/crop price ratios due to high taxes on fertilizers and crops (Lavado and Taboada, 2009). The widespread use of conventional tillage during the 70's, 80's and part of the 90's, has also lead to a significant soil erosion. By the early 1990´s, soils have lost an average of 50% of the native OM content, the main S reservoir of the soil (Álvarez *et al.,* 2009; Lavado and Steinbach, 2010). At that time, fertilizer use in the Pampas region gradually began to grow and a great technical progress started, which has lead to a strong increase in crop productivity. Among recent technologies, use of transgenic crops, herbicides, pesticides and fertilizers can be pointed as the most critical ones. In addition, no-till farming systems have shown a significant growth in recent years (Álvarez and Steinbach, 2009; Lavado and Taboada, 2009). The intensification of the cropping systems under degraded and/or low OM soils rapidly promoted the appearance of S deficiencies and crop yield responses to S applications in the Pampas agro-ecosystems. The first evidences of grain responses to S fertilization were found in the southern region of Santa Fe (Casilda) in soybean (Martínez and Cordone, 1998; Cordone *et al.,* 2002). After those pioneer field experiments, it took place a sharp expansion of S deficiencies to other regions and crops (Torres Duggan *et al.,* 2010; Torres Duggan and Rodríguez, 2011).

With regards to S diagnosis issues, many studies have been carried out in the Pampas region to evaluate different S soil testing methods for diagnosis proposes. Most of the experimental networks conducted did not show a correlation between grain yields and the sulfate content in the soil or soil properties (OM, texture) or management indicators (years under continuous agriculture) (Gutiérrez Boem, 2010). Nowadays, there is not a clear critical SO_4^{2-}-S threshold to be used for S diagnosis at regional scale in the Pampas. There are however, some exceptions of recent field studies that have reported a critical SO_4^{2-}-S threshold of 7 mg SO_4^{2-}-S kg^{-1} (Espósito *et al.,* 2008) or 10 mg SO_4^{2-}-S kg^{-1} at the topsoil (0- to 20 cm soil depth) (García *et al.,* 2010). The difficult in calibrating a S soil test method, would be related to different factors such as the sulfate content in deep layers of the soil (not included when only the upper soil layer is considered), difference in analytical methods, sulfate content in water table, etc. Because of this problem, different indicators has been proposed to evaluate the S status of the soil and address S fertilization: SOM; background of regional evidence of yield responses to S applications; soil degradation features; crop productivity; evidence of crop yield responses to N and P (Martínez and Cordone, 1998; *Cordone et al.,* 2002; Martinez and Cordone, 2005; Gutiérrez Boem, 2010).

Overview of fertilizer use and sulfur application

The continuous increase in crop productivity was possible through a better (more efficient and effective) and higher use of fertilizers (Stewart *et al.,* 2005; Álvarez *et al.,* 2012). As stated, the fertilizer consumption in Argentina has grown from 1.8 million MT in 1999 to 3.7 million MT in 2011 (García, 2012). The fertilizer demand is primarily driven by the main four crops grown in the Pampas (wheat, maize, soybean, sunflower), accounting for a total of 75% of the overall fertilizer consumption registered in the entire country (Melgar, 2005). Table 1 shows the average nutrient rate applied and the proportion of the cropped land under fertilization for the main field crops of Argentina, most of them (70-80%) grown in the Pampas region. As can be observed, only 40% of the wheat cropped area and 50% of the maize and soybean cropped area receives S application. The lesser S application in sunflower is related to its low average yields (1.85 ton ha^{-1} at country level; Hall *et al.,* 2012) compared to yield productivity levels achieved with cereal crops and soybean at farm level. As sunflower productivity becomes higher (*e.g.* grain yields > 3 ton ha^{-1}) an increase in the S fertilization response frequency would be expected that yield responses to S applications become more frequent in this crop. The lower percentage of cropped land that receive S applications compared to N or P for wheat and maize can be associated with the more recent fertilization history (García and Darwich, 2009).

Soybean is a particular case. This oilseed crop, traditionally, has received none or low applied fertilizer rates. This trend, however, has changed over recent times, as research information on yield improvements by balanced fertilization was transferred to farmers through the increasingly technical extension activities carried out by different organizations such as INTA, AACREA, AAPRESID, IPNI, and Universities, among others.

Notwithstanding the significant growth in the use of fertilizers in Argentina over recent years, there is still a gap between the crop nutrient requirements and the fertilizer rate regularly applied by farmers. Furthermore, nutrient balances are still negative in the argentine Pampas region. For S, the global negative budget for S is roughly of 7930 tons of S (Ciampitti and García, 2007; García and Darwich, 2009). The latter is evidencing an important challenge that should be addressed in order to achieve a more sustainable agro-ecosystems in the long-term.

Sulfur fertilizer consumption has grown harply over the past decades (Fig. 1). The higher S consumption rates were observed during the 90's, when a sharp adoption of the S fertilization took place in the main grain crops. Afterwards, S fertilization has expanded in a wide range of regions of the Pampas, including areas with high OM contents such as in the southeast of Buenos Aires (Reussi Calvo *et al.,* 2006; Pagani *et al.,* 2010). The statistical data used for the Figure 1, only includes the S fertilizer obtained by manufacture processes, such as ammonium sulfate (AS), single superphosphate (SSP), and others chemical

Table 1. Nutrient rate and percentage of the cropped area under fertilization for the main crops (wheat, maize, soybean, sunflower) grown in Argentina.
Tabla 1. Dosis de nutrientes y porcentajes de área fertilizada en los cuatro principales cultivos de grano de la Argentina (trigo, maíz, soja, girasol).

Crop	Fertilizer use		N	P	S
Wheat	Rate	kg ha^{-1}	46	16	10
	Fertilizer area	%	95	95	50
Maize	Rate	kg ha^{-1}	57	14	7
	Fertilizer area	%	90	90	40
Soybean	Rate	kg ha^{-1}	-	15	10
	Fertilizer area	%	-	50	50
Sunflower	Rate	kg ha^{-1}	15	9	5
	Fertilizer area	%	60	40	10

Source: Adapted from García and Salvagiotti (2009).

sulfate sources, not including local mined gypsum (Gy), an important S and soil amendment source (Ponce and Torres Duggan, 2005). According to unofficial information, about 51.000 MT of S as Gy is annually applied in Argentine cropping systems (Melgar, personal communication). It is noteworthy that during 2008 and 2009, a combination of different factors (mainly a strong drought and local economic constraints in the grain marketplace) brought a significant decrease in overall fertilization rates, including S fertilizers. However, after that time interval, the overall fertilizer consumption and S application have been recovered, reaching similar values to those reported prior to such events.

Sulfur fertilizer sources

The most common S sources applied by farmers in the Pampas are sulfate fertilizers (Torres Duggan and Rodríguez, 2009). Despite AS has been the traditional S source used in Argentina, in recent years, SSP has become an important source for soybeans, providing P and S to the crop. Additionally, Gy ($CaSO_4.2H_2O$) is a widespread S fertilizer (García and Salvagiotti, 2009). This source is obtained from local mining companies (Ponce and Torres Duggan, 2005). Compound fertilizers having S as sulfate and elemental sulfur (ES) into their granules are also used, but to a lesser extent. Although this kind of S sources has been gaining market over recent times, the published information about application rates and crops, are not currently available. Table 2 shows the nutrient content and physical state of the main S sources used in the Pampas region.

Liquid fertilizers are becoming important nutrient sources in the different cropping systems of the Pampas. The consumption of this type of fertilizers has been growing sharply over the past years (Melgar and Torres Duggan, 2005; Rodríguez and Torres Duggan, 2012). Ammonium thiosulfate (ATS) and UAN solutions (*e.g.* 32% of N) are the most commonly fluid sources applied by farmers. In addition, these two fertilizers are often blended in order to formulate a fluid fertilizer mix, with different N and S concentrations (Torres Duggan and Rodríguez, 2011). According to recent estimations, about 20% of the current national N consumption comes from UAN and/or UAN-ATS formulations (García and Darwich, 2009). These formulations have usually 80% of UAN and 20 % of TSA.

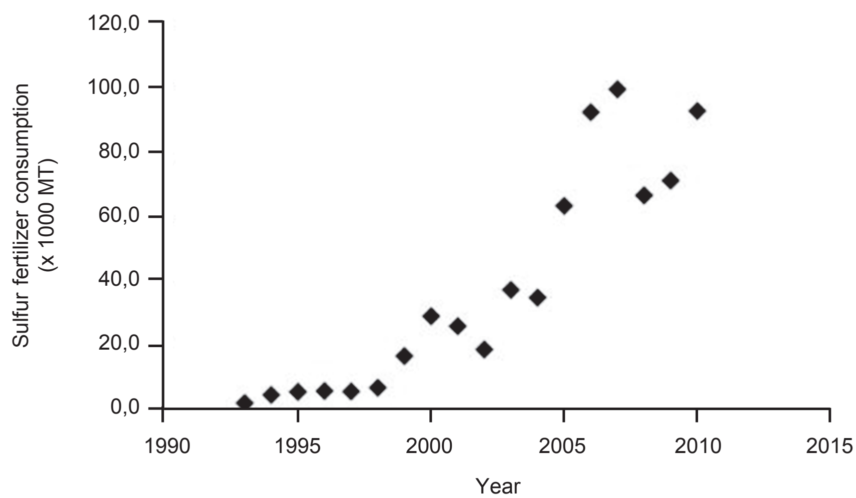

Figure 1. Sulfur fertilizer consumption in Argentina (from IPNI Southern Cone and Fertilizar AC).
Figura 1. Consumo de fertilizantes azufrados en la Argentina (en base a IPNI Cono Sur y Fertilizar AC).

Table 2. Main S fertilizer sources used in the argentine Pampas region.
Tabla 2. Principales fuentes azufradas utilizadas en la Región Pampeana argentina.

Source	S chemical form	S content (%)	Other nutrients	Physical state
AS (1)	SO_4^{2-}	24	N: 21%	Solid
Gy (2)	SO_4^{2-}	15-18	Ca:22%	Solid
SSP (3)	SO_4^{2-}	12	P: 9%	Solid
ES (4)	S^0	80-100	-	Solid
ATS (5)	$S_2O_3^{2-}$	26	N: 12%.	Liquid

Source: from Fertilizer Manual (1998); Gowariker *et al.* (2009) and Til (2010). (1): ammonium sulfate. (2) gypsum. (3) single superphosphate. (4) elemental sulfur (mostly micronized and incorporated into NPS granules of compound fertilizers). (5) ATS: ammonium thiosulfate (applied mixed with UAN solutions, in different ratios).

Recent research results on the evaluation of sulfur sources and rate effects

Over the past ten years, significant research information has been generated on the best management practices (BMPs) related to S fertilizer use for different cropping systems in the argentine Pampas, evaluating different issues such as optimum economical rate, soil testing and diagnosis, and interactions with other nutrients, among others. Regarding technological issues, most studies focused on the evaluation of crop yield responses to the application of different S fertilizer sources (Table 3).

Table 3. Field research information on the evaluation of crop response to different sulfur sources and rates for grain crops in the Pampas region.
Tabla 3. Resultados de investigaciones realizadas sobre la evaluación de la respuesta de los principales cultivos a diferentes fuentes y dosis de fertilizantes azufrados en la Región Pampeana.

Crop	Source	Rate kg S ha^{-1}	Yield Response kg ha^{-1}	Rate effect	Source effect	Reference
Wheat/ Soybean	Gy	(1)	Soybean=217-620 Wheat=130 (3)	NE	NE	Salvagiotti *et al.* (2004)
Wheat	Gy	15	625 kg ha^{-1}	NE	NE	Reussi Calvo *et al.* (2006)
Soybean	AS, Gy	15	160-500 kg ha^{-1}	NE	Ns	Gutierrez Boem *et al.*(2007)
Wheat	AS, Gy SSP	15 and 30	495 kg ha^{-1}	Ns*	Ns	Torres Duggan *et al.* (2006)
Wheat	ES (4)	24 and 40	208-465 kg ha^{-1}	Ns	Ns	Tysko and Rodríguez (2006)
Wheat	AS, ES (4)	10 and 30 (year 1) 15 and 30 (year 2)	600-1400 kg ha^{-1}	Ns	Ns*	Torres Duggan *et al.* (2010)
Soybean	AS, ES (4)	10 and 30 (year 1) 15 and 30 (year 2)	297-558 kg ha^{-1}	Rate x year x source	Rate x year x source	Torres Duggan (2011)
Maize	Gy	5-20	492-755 kg ha^{-1}	Variable across sites	NE	Pagani *et al.* (2009)
Wheat Maize Soybean (2)	SpS SpS SpS	17-25 17-25 17-25	234 kg ha^{-1} 1153 kg ha^{-1} 360 kg ha^{-1}	NE	NE	Garcia *et al.* (2010)

Notes: AS: ammonium sulfate ES: elemental sulfur. Gy: gypsum. SSP: single superphosphate. SpS: sulfate sources. (1) 20 kg ha^{-1} for double crop or for each crop (8 and 12 kg ha^{-1} for wheat and 12 for double cropped soybean). (2) Full-season and double cropped soybean. (3) Disease problems. (4) Applied at sowing time. NE: not evaluated. Ns: not significant *(Pe ≥ 0.05)*. *Differences between sites.

In general terms, small differences have been observed and documented among sulfate fertilizers in terms of agronomic effectiveness (differences in yields, when two or more fertilizer sources are compared at the same nutrient rate and placement), and agronomic efficiency (kg grain response kg^{-1} of applied nutrient) for wheat (Torres Duggan *et al.,* 2010) and soybean (Gutiérrez Boem *et al.,* 2007). Nevertheless, for maize and sunflower (*Helianthus annuus* L.), the information regarding this matter is scarce. Regarding S application rates, maximum grain yield responses to S application were observed applying 15 to 20 kg S ha^{-1} for the main grain crops (Torres Duggan *et al.,* 2010). Furthermore, some field research studies have shown interaction between S rates and sites (Pagani *et al.,* 2009; Torres Duggan, 2011).

The advantage of sulfate fertilization is that it can provide S in the plant available form and, that the sulfate is easily incorporated in multi-nutrient fertilizers, which is a cost-efficient way of fertilizer application. However, in some cases their use may give an unbalanced nutrient supply. One case is the widely used AS, where its use as a N source applies much more sulfur than typically required (Eriksen, 2009). Contrastingly to the abundant research information on sulfate fertilizer sources, current research regarding the agronomic effectiveness of the ES is relatively scarce.

New developments of ''Sulfur Enhanced Fertilizers'' (SEF) have been carried out by the fertilizer industry worldwide (Prochnow and Blair, 2010). In accordance, international fertilizer companies are marketing these fertilizers in South America, mainly in Brazil and Argentina. The technology used to manufacture SEF fertilizers is done mainly by adding the ES onto conventional granules of NP fertilizers (*e.g*. ammonium phosphate sources). Because of the high S content of the ES (almost 100%), N and P concentrations of compound fertilizers are not decreased during manufacture processes, compared to the addition of S using sulfate fertilizers (*e.g*. AS or gypsum) (Chien *et al.,* 2009). The incorporation of micronized ES particles into conventional NP or NPK compound fertilizers is the most significant S product innovation over recent times. This technology represents a progress in terms of both handling security (reduction of explosion risk, frequent in the old coating technology) and agronomic aspects. By applying this granulation technology,micronized ES of even less than 40 µm can be added upon the granules matrix of compound fertilizers. This technology has significant improvements compared to previous product developments: i) higher oxidation rates, ii) higher concentration of S in all granules, and iii) higher P:S, ratio more adjusted to crop requirements (Sinden, 2012).

The ES must be oxidized in the soil and converted to sulfate which is the available S form for the plans. The ES oxidation process depends on several factors such as environmental conditions, soil properties, application methods, chemical and physical properties of the ES, and crop, among others (Lefroy *et al.,* 1994; Girma *et al.,* 2005; Horowitz, 2007). The latter demonstrates the complexity of the ES oxidation process. The progressive releasing of the S would be an advantage mainly under sandy soils or/and high rainfalls conditions, when sulfate fertilizers may be lost by leaching processes (Til, 2010). Under template conditions and low risk of leaching processes, differences in agronomic effectiveness between sulfate and ES are related to the capacity of the ES to oxidize in the soil and provide S available to crops. A practical way to increase S availability is to reduce the ES particle size. This practice enhances the S oxidation rate and increases its availability for plants, by increasing the surface contact between the soil and the fertilizer particle (Schoneau and Malhi, 2008).

Recently, promising results have been documented on crop yield responses to ES application in the Pampas. In this regard, in a two-year study conducted in eight wheat field trials and during nine full-season soybean experiments, Torres Duggan (2011) found similar agronomic effectiveness and efficiency between AS and micronized ES applied at sowing time. Pooling results from the two S sources, yield responses to S application were 600 and 1400 kg ha^{-1} in the first and second year, respectively for wheat, and 558 and 297 kg ha^{-1} in the first and second year, respectively, for full-season soybean. At site-specific conditions (*e.g.* low OM or drought events), AS outperformed ES presumably due to low oxidation rates. The grain yield responses observed during the first year were similar or even higher than the average values of S responses reported in the literature for Argentina and other countries, such as Brazil, India, and USA (Ganeshamurthy and Reddy, 2000; FAO, 2004; Chen *et al.,* 2005; Gutierrez Boem *et al.,* 2007).

Further research is needed in order to investigate crop response to S and S agronomic efficiency of the ES and other S sources in contrasting environmental conditions (climatic condition, soil type, etc.). As a preliminary conclusion from the information reported by Torres Duggan *et al.* (2010) and Torres Duggan (2011), it seems that central and northern areas of the Pampas' soils have suitable conditions for the oxidation of reactive forms of ES. In other regions, such as the southern or western areas of the Pampas, scientific information regarding this issue is lacking.

In the above-mentioned experiment, the small particle size used for the ES (200 µm) might have been a key factor for achieving high S agronomic efficiency in both soybean and wheat crops. According to the literature, the particle size is linked to the oxidation rate: small particle size promotes high oxidation rates (Boswell and Friesen, 1993). Nonetheless, the climate conditions regulate the oxidation rate, for example low temperature reduces ES oxidation rates. For this reason, lower agronomic performances of ES relative to sulfate sources may be observed in cold environments. Thus, higher S agronomic efficiency was documented for sulfate sources in the Great Plains of United States (Franzen and Grant, 2008), at lower temperatures than the Pampas's. The ES oxidation process steadily increases within a temperature range from 10 to 40°C, diminishing with temperatures lower than 4 °C (Blair *et al.,* 1993). In addition, the ES oxidation is a biological process affected by different microorganisms with diverse optimum temperature ranges to achieve the maximum biological activity. Temperatures from 25 °C to 40 °C are within the optimum range for most microorganisms. Additionally, soil moisture extremes (dry or saturated soils) can substantially reduce the ES oxidation rates, the optimum moisture availability being near the point of water field capacity, level that varies with soil type (Tisdale *et al.,* 1993).

Application methods

Although, research background on S application methods (placement, timing) is scant in the Pampas region, no differences among application moments (at sowing or at early stages of the crop) have been reported in field crops using sulfate sources (Diaz Zorita, 1998; Keller and Fontanetto, 1998). This may be related to the low adsorption capacity of the soils in the central area of the Pampas (*i.e.* Rolling Pampa and Inland Pampa) (Russi *et al.,* 2012). This context differ from high sulfate fixation soils such as Oxisols from Brazil, where banding applications outperform broadcasting placement and hence an increase in the S rate is necessary to improve the S use efficiency (Stipp and Casarin, 2010). Because of the above mentioned similar sulfur agronomic efficiency among different application methods for the Pampas' soils, farmers often apply S in a wide range of placement and timing strategies (Table 4).

With regards to ES application methods, research information on placements and timing effects is quite scant for the Pampas agro-ecosystems. Hence, it should be considered the international background on this matter. As before discussed in this work, ES agronomic effectiveness depends mostly on the particle size and dispersion capacity, temperature and soil water content. These factors should be taken into account for the ES selection in order to estimate the S release during the crop season (Til, 2010). When low temperature conditions at early crop stages are expected, it

Table 4. Sulfate application methods for grain crops in the Pampas region of Argentina.
Tabla 4. Métodos y momentos de aplicación de fertilizantes sulfatados en cultivos de granos de la Región Pampeana argentina.

Timing	Placement	Nutrients and fertilizer types
Pre-planting	Solid fertilizers: broadcasting. Liquid fertilizers: dribbled NS solutions	N, P and S (single or complex fertilizers, bulk blends)
At planting	Together with seeds or banding (2-5 cm below and/or to the side)	N, P and S (single and complex fertilizers, bulk blends)
After planting	Solid fertilizers: broadcasting or incorporated. Liquid fertilizers: dribbled	N, P and S (single and complex fertilizers, bulk blends and liquids)

Source: adapted from Prystupa *et al.* (2012).

should be necessary to provide S in sulfate form or it must be chosen a reactive form (low particle size), evaluating the oxidation capacity of such ES source at the site-specific condition (Boswell and Friesen, 1993). For doing so, it is necessary to know the oxidation capacity of the different ES products available in the marketplace under different regions and crops. This information is currently not available in the Pampas. Hence, and as a preliminary approach, it can be suggested some guidance for assessing ES placement and timing technological decisions. When site-specific conditions are restrictive for ES oxidation (*e.g.* low temperature and/or low soil water content): i) apply a sulfate fertilizer source; or ii) select a reactive form of ES that allow a rapid oxidation at early stages of the growing season and/or anticipate the application some days before sowing. This general guidance should be adapted for different crops, regions and environmental conditions. Further research on this matter is necessary.

The residual effect is other key factor to be considered in the S fertilization management. This process has been reported for both P and S in different regions and crops (Torres Duggan *et al.,* 2010; García *et al.,* 2010). These residual effects can be managed to provide S to the whole cropping system (*e.g.* double cropped wheat/soybean). Thus, farmers are able to apply S at the planting time of the first crop in the sequence (*e.g.* wheat) in order to provide these nutrients to the current and the following crop in the sequence (*e.g.* soybean). According to Salvagiotti *et al.* (2004), S use efficiency did not significantly differ from applying the nutrients at planting of the wheat for the wheat/double cropped soybean sequence or doing so at each individual crop. These residual effects indicate (indirectly) that the S soil fixation processes in the Pampas soils have low incidence. However, more research still needs to be done and specific studies should be carried out in order to confirm or reject these results.

With regards to liquid fertilizers, the most frequent application method used by farmers to apply NS solutions is dribbling the fertilizer on the soil surface (Torres Duggan and Rodríguez, 2011). These fertilizers are applied at different stages during the crop growing season (*e.g.* at planting, tillering of winter cereals, V5-6 stage of maize). Furthermore, the rapid adoption of liquid fertilizers experienced in Argentina was related to the advantages in the logistics (*e.g.* flexibility in fertilization timing) and also in agronomical aspects (*e.g.* lower N volatilization compared with surface urea application) (Melgar and Torres Duggan, 2005; Chien *et al.,* 2009).

Future research needs

It can be mentioned some knowledge gaps linked with diverse issues associated to S fertilization management in the Pampas region of Argentina. Some of the research priorities to be investigated are as follows:

(i) Sulfur uptake, S use efficiency, and grain yield under different S application placement and timings for different grain crops. More specific research should be performed to determine the best management practices associated to the use of the S fertilizers, and considering the potential uses as starters, in-season fertilizations, and foliar S applications. The right timing, placement, rate, and source are not only pursued through the use of S by itself but more for the fertilizers that combine more than one single nutrient (N-P-S formulations, K plus other micronutrients, etc.). Lastly, research performed at the cropping system-level should consider not only the interaction of the fertilizer with the soil, but also the efficiency in the crop uptake associated to the soil nutrient supply, and the synchronization with the crop demand.

(ii) Agronomic effectiveness of ES in relation to sulfate sources in different crops, soil types, and environmental conditions. Also, ES oxidation rates and regulating factors at local soil and environmental conditions, in order to obtain a local model to address the use of this kind of sources in different crops, and regions of the Pampean agro-ecosystems. In addition, more information should be properly identified and acknowledged as related to the chemical and physical properties of the ES. The identification and analysis of different field research trials with a common basis for the ES properties would allow the adequate comparison among experiments and can improve the understanding of this S source and its effects in a more regional scale.

Additionally, more research is necessary regarding basic processes related to S dynamic in the soil-plant system. Although that issue is not analyzed in this manuscript, it represents a quite important framework for applied research projects, leading to a better understanding of the whole behavior of S fertilizers in agro ecosystems.

CONCLUSION

Sulfur fertilization has increased sharply over the past years. Most solid S fertilizers applied by farmers are sulfate sources (*e.g.* AS, gypsum, etc.), showing similar agronomic effectiveness among sources and application methods. Recently, some field research studies showed promising results using micronized ES as an S source for many grain crops. Nonetheless, this product is at a very incipient-stage and more research is needed in this topic. Liquid fertilizer (*e.g.* UAN, ATS formulations) consumption has grown significantly during the past decades. The use of these fertilizer sources is becoming a more frequent practice in fertilization programs, mainly linked to logistic and agronomical advantages. However, more research is needed to address the use of this technology in the Pampas.

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