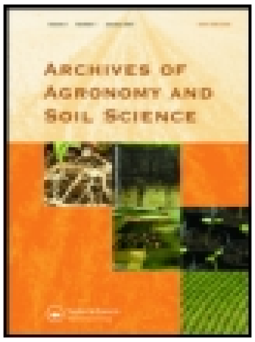

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Sulfur management strategies to improve partial sulfur balance with irrigated peanut production on deep sands

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Abstract

Sands have favourable physical properties for harvesting peanut, but improving S and water use efficiency on these soils remains a challenge. We studied partial S balance in irrigated peanut crops on sands of Central Vietnam to identify key factors of S fertiliser management affecting S inputs and outputs. Field trials were conducted in the spring seasons of 2015 and 2016 to determine the effects of S application rates (0, 15, 30, 45 kg ha^{-1}) on peanut yield and partial S balance. Sulfur balances were negative (-28.3 to 5.6 kg S ha^{-1}) at rates < 30 kg S ha^{-1}, while at higher rates of S fertiliser application that produced maximum pod yield (30 - 45 kg S ha^{-1}), three of four sites showed neutral to slightly

positive S balance (1.5 - 5.6 kg S ha^{-1}). The negative partial S balance decreased with increasing S rates but was mostly attributable to the large S removal in peanut shoots (9.7 - 22.3 kg S ha^{-1}) which are used on farms for animal feed. The negative partial S balance results in depletion of soil S reserves and hence efficient recycling of S on farms is critical for sustainable crop production on sands of VN.
Keywords: Deep sands, Haplic Arenosols, leaching, sulfur fertiliser, sulfur budget

Introduction

Sulfur may severely limit crop yield and impair the quality of agricultural products (Jackson 2000; Malhi and Leach 2002). Crop responses to applied S have been widely reported in temperate to tropical climates (Blair 1979; Eriksen 2008). Occurrence of S deficiency is strongly affected by soil characteristics: it is especially prevalent on soils that are low in organic matter, where S release by mineralization will be limited, and on coarse-textured soils where SO_4^{2-}-S leaches from the rooting zone over time (Riley et al. 2002; Franzen and Grant 2008). Sulfur requirement is the highest in oil seed crops followed by pulses and least in cereals (Meena et al. 2007). Oil seed crops remove 12 kg of S t^{-1} compared to 8 and 4 kg S t^{-1} of seeds or grains of pulses and cereals, respectively. Among the main crops in the semi-arid tropics, peanut is one of the most demanding for sulfur (Marschner 1995).

Sulfur deficiencies in Central Vietnam were initially identified on sands which cover 500,000 ha (Bell et al. 2015a). These soils are particularly susceptible to S deficiency because of intense summer rainfall and low organic matter content (Hoang et al. 2012). In addition, over irrigation is widespread among peanut farmers in Phu Cat district, Binh Dinh province, South Central Coast Vietnam (SCC VN) (Bell et al. 2015b). Hence, leaching of S may be depleting S availability for crops. McGrath and Zhao (1996) indicated that sulfur has not been studied thoroughly under irrigated conditions despite S deficiency being reported with increasing frequency over the past several years all over the world.

Sulfur is an important component of complete and balanced crop nutrition, and has justifiably gained more attention in recent years. Understanding the S budget is of crucial importance for S management in agroecosystems. Crop offtake and S leaching are the largest outputs of S in agroecosystems. The S supply from internal sources, i.e. net mineralisation of soil organic matter, crop residues and animal manure, is important for the matching of S supply to S demand, but difficult to predict (Oenema and Postma 2003). Therefore, the objective of this study was to (i) evaluate the effect of different S management practices and rates on the yield of peanut and (ii) to examine short-term changes in soil characteristics and S balance in peanut fields in sandy soil of SCC VN.

Materials and methods

Field experiment sites and treatments

In Phu Cat district, Binh Dinh province, SCC VN field experiments were conducted in Cat Hiep commune (14°03′05″N and 109°99′52″E) and Cat Hanh commune (14°05′46″N and 109°00′16″E), respectively, on Haplic Arenosols with > 95 % sand and < 5 % clay (Bell et al. 2015a). The sites' climate was tropical savannah, characterized by monsoon rainfall from September to December which accounts for most of the annual 2,300 mm of rainfall, whilst average temperature is 26.7°C. Only 44 - 88 mm of rain fell during the peanut growing seasons. Topsoils (0 - 20 cm and 20 – 40 cm) before the experiments at two sites were acidic (4.5 – 4.9 pH_{KCl}), and low in total organic carbon (4.2 – 8.9 g kg^{-1}), total N (0.08 – 0.20 g kg^{-1}), total P (0.09 – 0.11 g kg^{-1}), total K (0.5 – 1.0 g kg^{-1}) and available S (1.8 – 2.0 mg kg^{-1}) (Bigham 1996).

The study comprised two field experiments with four S rates of application for peanut (0, 15, 30 and 45 kg S ha^{-1}). A randomised complete block design was applied, with three replications. Each plot had an area of 10 m^2. All experiments were supplied with 40 kg N, 80 kg P, 50 kg K, 8 t of FYM and 500 kg of lime ha^{-1}. Nitrogen, phosphorus, potassium were applied as urea (46% N), thermophosphate (7% P) and potassium cloride (50% K), respectively. Sulfur was applied as amonium sulphate (24% S). The amount of urea fertiliser added was adjusted based on N added in amonium sulphate, so that all treatments received 40 kg N ha. Organic admendment was applied as cattle manures with average nutrient concentrations in 2 sites and 2 seasons as follows: pH 7.1; 1.05 N%; 0.29 P%; 0.42 K%; 0.18 S%, 59% DM) in equal amounts to all treatments. Lime ($CaCO_3$ – 40% Ca) was applied two weeks before sowing as a broadcast application and incorporated to a soil depth of 20 cm. The required amount of organic amendments and phosphorus were only applied at sowing by row application. Sulfur was also applied by incorporation into soil at sowing together with organic amendments and phophorus. The N and K fertilisers were also applied as row applications at two stages of the plant growth: (1) one third of the amount at full expansion of the third leaf (12 days after sowing) and (2) the remaining two thirds of the amount just prior to flowering (35 days after sowing). Peanut cv. Ly, a variety frequently used in Central Vietnam, was sown on 24 December 2015 and 28 December in 2016 following harvest of a cassava crop. Peanut seeds were planted at 30 cm between rows and 10 cm between seeds to reach a plant population of about 330,000 plants ha^{-1}. Peanut was irrigated manually by hose pipe when soil surface became dry and each event was stopped when water infiltrated to a depth of 5 – 7 cm. A total of 4,500 m^3 ha^{-1} for each crop (calculated from the rate of water flow in the hose and the duration of each irrigation event) was applied in 35 irrigation events.

Partial S balance study

To assess partial S balance under a peanut crop, field level nutrient gains and losses were assessed and referred to as input and output data, respectively.

S inputs

The inputs by chemical fertiliser and manure *(IN 1 & 2*) were recorded by weight in the field before application. Samples of both were collected for total S analysis in the laboratory by digestion with HNO_3 and $HClO_4$ through the turbidimetric method (Chaudhary and Cornfield 1966). The supply of S to each crop was calculated in kg per hectare.

Rainwater samples *(IN3)* were collected during rainfall events in the field. The data on the amount of rainfall was obtained from the weather station at Phu Cat district (7 km from the experimental sites). Total SO_4-S in rain water was determined on a filtered and unacidified sample with an ion chromatograph using an anion-ion exchange separator column. On entering a suppressor column, the eluting base, for example, NaOH, is removed by the acid resin, and the analyte anions (A-) are converted to their acids, which pass through the suppressor column and into a flow-through conductivity cell where they are detected (Fishman and Pyen 1979).

Irrigation water samples *(IN4)* from each irrigation time were collected directly in the fields at each site in spring seasons 2015 and 2016. Water samples were first filtered and SO_4^{2-}-S in irrigation water was measured by ion chromatography. The volume of irrigation water applied into the experimental area was calculated at each time of application.

S outputs

Peanut pod, leaf and stem *(OUT 1&2)* S concentrations were analyzed to calculate the quantities of S in plant material removed from the field. Stem and leaf were defined as the part of peanut plant left after removing pods during harvest. Weights of stem and leaf dry matter were measured from 1 m^2 sampling area of each plot, after excluding dead, diseased, insect damaged or mechanically injured plants. Selected plants were uprooted, the pods and the basal part of the shoot were washed with tap water and placed in paper bags. Samples were dried in a forced-draft oven at 70° C (± 5° C) until a constant dry weight was obtained (in 2 days), ground to the size of 0.25 mm, and all results were triplicate averages expressed on a dry matter basis. The S content of plant material was determined after digestion in HNO_3 and $HClO_4$ by turbidimetry (Chaudhary and Cornfield 1966).

Sulfur leaching *(OUT 3)* was assessed by analysing S in the soil leachate. Leachate samples were collected at 3 and 25 days after S application from the container placed 30 cm below the soil surface (Hoang et al. 2019a). The leachate was collected using a 25 cm diameter plastic bucket placed at 30 cm depth from surface with a fitted mesh to prevent soil entry into the bucket. A plastic tube was fitted to the bottom of the bucket to withdraw the leachate using a syringe. Leachate was collected at each sampling time and the volume of leachate was measured using a cylinder. Leachate samples were filtered and analyzed for soluble SO_4^{2-}-S by ion chromatography.

Partial S balance

To assess partial S balance under peanut crops at field level, S gains and losses were summed from input and output data, respectively using a similar approach to Hoang et al. (2019a). Hence, the total S balance (M) in an agroecosystem at its steady state would be at equilibrium when $M_{input} - M_{output} = 0$. Losses through volatilization and erosion were not considered to be significant for this study.

Soil analysis

Five soil samples were collected from the 0 - 20 cm layer of each plot and combined to make a composite soil sample. Immediately after collection the samples were sealed in plastic bags and transported to the laboratory for removing root detritus and the soil air-dried and ground to pass through a 2 mm sieve. Soil was digested by KNO_3 and HNO_3 in 3 hours combustion at 550°C and then total soil S was determined by the turbidimetric method of Chaudhary and Cornfield (1966). Available S was analysed by using monocalcium phosphate as extracting solution (Motsara and Roy 2008).

Peanut yield assessment

At 98 days after sowing, a quadrat measuring 4 m^2 was used for harvesting peanut growth in each plot to assess pod yield and other components (dry matter, no of pods, weight of shell etc).

Statistical analysis

Analysis of variance (ANOVA) was calculated using a factorial design, where years were treated as the block variable; replications as the replication variable and S rates (0, 15, 30 and 45 kg ha^{-1}) as the treatment variable. Based on significant effects in the ANOVA, differences among means were examined by the Tukey test (0.05) and standard errors (SE) were calculated using SPSS program version 20.

Results

Shoot plant S and soil S

There were close positive relationships between S concentration in plant shoots and fertiliser S rates in all four experiments in two seasons (R^2 from 0.88 – 0.97) ($p<0.01$) (Figure 1). The highest S concentration was at rate of 45 kg S ha^{-1} but concentrations varied between the sites (1.8-2.0 g kg^{-1} in Cat Hanh commune and 2.5-3.7 g kg^{-1} in Cat Hiep commune). The lowest S concentration in plant shoots was in control treatments in both crop seasons and communes.

[Figure 1 near here]

Total soil S increased from 2.4 to 3.4 mg kg^{-1} in Cat Hanh commune and from 3.1 to 4.1 mg kg^{-1} in Cat Hiep commune (Figure 1). As with shoot S, total soil S was highest after the application of 45 kg S ha^{-1}, that is 3.3-3.4 mg kg^{-1} at Cat Hanh commune and 3.6-4.1 mg kg^{-1} at Cat Hiep commune, although differences compared with the application of 30 kg S ha^{-1} were not significant at Cat Hiep commune. At each site there were close relationships between S rate and soil S (R^2 from 0.75 to 0.98) ($p<0.01$).

Partial S balances

Total inputs of S, on average, ranged from 7.8 to 52.8 kg S ha^{-1} in spring season 2015 and 8.9 to 53.8 kg S ha^{-1} in spring season 2016 (Table 1). The total inputs of S depended mainly on amount of S fertiliser application with additional inputs from organic manure (7.4 to 8.0 kg S ha^{-1} in spring season 2015 and 8.6 to 8.7 kg S ha^{-1} in spring season 2016), irrigation and rainfall water. Total outputs of S were from S loss by leaching and removal by products. Total average outputs of S ranged from 34.2 to 54.1 kg S ha^{-1} in spring season 2015 and 28.2 to 50.6 kg S ha^{-1} in spring season 2016. There was significant S removal in shoots at all rates of S fertiliser application, but the maximum S removal in peanut leaf and stem were 18.4 – 19.2 kg S ha^{-1} at rate of 45 kg S ha^{-1} application. Similarly, S removal by pod increased significantly with increasing rate of S fertiliser application. Hence, maximum S removal by pod at rate of 45 kg S ha^{-1} application was 12.3 – 14.2 kg S ha^{-1} in spring season 2015 and

14.1 – 15.5 kg S ha^{-1} in spring season 2016. By contrast, in control plots pod removal of S ranged from 4.7 – 6.3 kg S ha^{-1}.

[Table 1 near here]

The negative partial S balances, which were largely due to removal of all peanut leaves and stems and leaching, were almost fully reversed at the highest rate of S fertiliser application, with values increasing from -26.4 kg S ha^{-1} (control) to -0.7 kg S ha^{-1} (45 kg S ha^{-1}) in spring season 2015 and – 19.5 kg S ha^{-1} (control) to 3.2 kg S ha^{-1} (45 kg S ha^{-1}) in spring season 2016 (Table 1). Positive partial S balance could have occurred at all rates of S fertiliser application excepting for control (no sulfur application) by avoiding S removal in stems and leaves (9 – 34.1 kg S/ha), in pods (12.8 – 40.2 kg S/ha), or by leaching (5.1 – 40.5 kg S/ha) in both seasons and communes.

There were close relationships between partial S balance and S rate application (R^2 from 0.74 – 0.99) as well as with plant S (R^2 from 0.75 to 0.86) in both communes and seasons (Figure 2 a1-a2 and b1-b2).

[Figure 2 near here]

Peanut shoot dry matter, yield attributes and yield

Dry matter yield and pod yield increased with the increase in S rate. Hence, maximum dry matter yield (7.78 to 8.78 t ha^{-1}) was recorded at 45 kg S ha^{-1} application at both communes and seasons (Table 2). The effect of S levels of application on pod yield was significant in Cat Hiep but not Cat Hanh commune in both seasons (Table 2). Harvest index decreased with higher rates of S application in Cat Hiep commune (from 50.7 to 48.3% and 47.2 to 44%). Pod numbers increased following S fertiliser rates application and produced significant differences among treatments in both communes in spring 2016 (12.6 – 18.7 pods $plant^{-1}$). The 100-pod weight was not significantly different among treatments in both seasons and communes. Shelling percentages were higher than 70% at all treatments but were highest at 30 – 45 kg S ha^{-1} application in Cat Hiep commune in summer season 2015 (79%).

[Table 2 near here]

There were close relationships between i) pod yield and S rate application (R^2 from 0.91 to 0.98) (Figure 3 a1, a2), ii) pod yield and plant S concentration (R^2 from 0.65 to 0.96) (Figure 3 b1, b2), and iii) pod yield and soil S concentration (R^2 from 0.80 to 0.98) (Figure 3 c1, c2).

[Figure 3 near here]

Discussion

Negative partial S balance

Negative partial S balance was found in all experiments with no S fertiliser applied, and at S rates up to 30 kg S ha^{-1}. Even at rates of S required to achieve maximum pod yield of peanut, there was generally negative partial S balance. At 45 kg S ha^{-1}, the partial S balance was close to neutral (-0.7 to 5.6 kg S ha^{-1}). The negative partial S balance can be largely attributed to removal of all peanut crop residues which is the prevailing practice in Central Vietnam due to their value as animal feed (-27.9 - 6.6 kg S ha^{-1}). Similarly, Hoang et al. (2019b) concluded that peanut shoot residue removal from fields to feed cattle was the major cause of negative K balances. Based on our calculations if all the peanut crop residues were retained in the field, neutral partial S balances would be achieved with much lower S fertiliser rates of 17.9 - 33.9 kg S ha^{-1}. With further S management changes, such as decreased leaching, the fertiliser S requirement could be further decreased to 12 - 16 kg S ha^{-1}, which is the amount of S removed in pods for maximum peanut yields, which in this study was in the range of 3.3 - 3.9 t ha^{-1}.

According to Dick et al. (2008), peanut with yield of 4.5 t ha^{-1} removed 24 kg S ha^{-1} in crop residues: this result is similar with our study. Besides peanut, S removal also occurred in other crops growth in rotation with peanut like cassava and rice in SCCVN. Cassava removed 14.0 - 19.3 kg S ha^{-1} when harvested after 12 months with cv. M Ven 77 in Columbia (Howeler 1985). Rice grain removes 1-3 kg S t^{-1} (Bell 2008). Higher yielding fields have a higher rate of sulfur removal when compared with lower producing fields.

Total S uptake by the groundnut–wheat system recorded marked improvement with increasing level of sulfur to 40 kg S ha^{-1} during each of two years (Noman et al. 2016). The positive balance over the initial value as S applied increased up to 40 kg S ha^{-1}. Patel et al. (2007) also reported residual effect of 20 kg S ha^{-1} applied to preceding crop. The gross S balance was negative in light texture soil of Thailand if no S fertiliser was applied and was even negative if 8 or 16 kg S ha^{-1} is applied and the plant residues were not returned (Blair and Lefroy 1987). The negative S balance with applications of 8 and 16 kg S ha^{-1} when the residues are not returned to sands of Thailand emphasise, like the present study, the importance of residue management in the S balance.

On the sands of SCC VN, S lost by leaching is rather high compared with other outputs. This result is in agreement with Riley et al. (2002) and Kirchmann et al. (1996) who assessed S leaching from lysimeters (56 cm deep, 60 cm deep) with different rainfall amounts (787 mm, 470 mm and 660 mm) and found that most of the gypsum S had leached from the soil in the first year after application; 72% of applied ammonium sulfate was lost to the drainage water in the first year; 88% of S added as $(NH_4)_2SO_4$ was leached from the soil. Sulphate leaching was 19 - 53 kg ha^{-1} annually on sandy soil in Croatia (Mesic et al. 2007). Chien et al. (2011) indicated that sulfate-S is relatively mobile in most soils (similar to nitrate) because it has a double negative charge and is repelled by the negative charge of the soil, unlike cations. Although SO_4-S can bind to variable charge sites on iron and aluminum oxyhydroxides and kaolin in acid soil, these surfaces are more likely to bind phosphate in preference to SO_4-S. As a result, SO_4-S is easily leached from acid soils, especially sandy soils (Camberato and Casteel 2017).

Our results indicated that S contents in rainfall and irrigation water were small by contrast with inputs from organic and inorganic fertiliser applications and with average crop removal of S in the present study (12-16 kg ha^{-1}). Sulfur concentrations in rainwater, however, vary widely, and generally decline with increasing distance from the coast or from industrialized areas (Lefroy et al. 1992).

Tandon (1991) reported that S added to soil through precipitation (0.6 kg ha^{-1} year $^{-1}$) and irrigation (0.5 kg ha^{-1} $year^{-1}$) was small relative to its addition through fertilisers and manures.

Well water used for irrigation may also contain a considerable amount of sulfate. Yamaguchi (1999) reported that a range of 0.2 to 20 mg S L^{-1} in irrigation and river water, but most of the irrigation waters analyzed in Malaysia and Indonesia contained less than 3 mg S L^{-1} (Lefroy et al. 1991). Elsewhere, S deposition from rainfall and irrigation may provide enough S to meet plant demand at many sites (Abedin Mian et al. 1991; Haque 1995).

Sulfur additions through fertilisers and organic manures varied according to their composition (Sager 2012). Amendment of soil with biosolids, manures, and composts will generally increase available sulfur. Biosolids may contain 0.3 to 1.2 % S (Miller 1993). Most animal manures contain 0.25 to 0.30% S except for sheep manure and poultry manure, which average approximately 0.35% and 0.50% S, respectively (Banwart and Bremner 1975). The mean S content in farmyard manure (FYM) is around 1 kg S t^{-1} FYM.

S rate in relation with shoot and soil S

Our results indicated that shoot S contents increased linearly with increasing rates of S fertiliser application. According to Balota (2014), an application of 11 - 22 kg S ha^{-1} should suffice for peanut: they also proposed the leaf S sufficiency concentrations were 2 – 5 g kg^{-1}. In our study, the plant S was 1.2 (0 kg S ha^{-1}) - 3.7 g kg^{-1} (45 kg S ha^{-1}) indicating S deficiency without S fertiliser addition. Groundnut absorbs on an average of 11 - 22 kg S ha^{-1} to produce one ton of seed (Kanwar and Mudahar 1984). Our results indicated that application of 45 kg S ha^{-1} recorded significantly higher S content in stem and leaf (18.4 – 22.3 kg ha^{-1}), pod (12.2 – 15.5 kg ha^{-1}). Similar result has been reported by Tageldin et al. (1987); Shubhangi et al. (2014), S content ranged from 0.24 to 0.18 % in soybean seed and 0.24 % in stem and lead by varied levels of S. Application of S increased the total S uptake by soybean from 13.1 to 19.1 kg ha^{-1} with rise in S levels from 0 to 60 kg ha^{-1}.

Soil S also increased with the increasing rate of S fertiliser application in our results especially at rate of 45 kg S ha^{-1}. Skwierawska et al (2008) pointed out that fertilisation with 80 and 120 kg S ha^{-1} caused increased SO_4^{2-}-S accumulation in soil compared to the NPK and control. High concentration of SO_4^{2-} in the soil solution of the uppermost soil layer (Eriksen 1996) may also be caused by the application of S containing fertilisers and other S inputs. Further, surface soil material adsorbs less SO_4^{2-} than does subsoil material, because organic matter and phosphate accumulations are thought to be major factors, which block SO_4^{2-} adsorption sites (Limousin et al. 2007). Mineralization of high-S crop residues may also contribute available S to subsequent crops (Jackson 2000; Grant et al. 2003).

S rate and effects on yield attribution

Application of S up to 45 kg S ha^{-1} caused significant increase in peanut yield components and pod yield. Improvement in peanut pod yield (3.67 t ha^{-1}) may be traced to improvement in pod number per plant (18.8 pods plant^{-1}) and also to improvement in harvest index (45%) with increasing rate of S application to 45 kg S ha^{-1}. Singh et al. (1991) reported that application of 30-40 kg S ha^{-1} to peanut was more beneficial. Application of 1 kg of nutrient S produced 12.9 kg more pod. Chaubey et al. (2000) claimed that application of 45 kg S ha^{-1} would be sufficient for higher pod yield of groundnut compared to other rates. An application of S at 30 kg ha^{-1} proved superior to other levels in respect of yield, protein content and S uptake by groundnut. The effectiveness of S sources was in the order of gypsum>single super phosphate>elemental S (Venkatesh et al. 2001). Singh et al. (1991) reported that 50 kg of gypsum ha^{-1}applied to the pegging zone at flowering increased pod yield by 20.5 %. Supply of S in adequate amount at 60 kg ha^{-1} for peanut also helps in the development of floral primordial which results in the development of pods and kernels in plants (Pancholi et al. 2017). Similar findings have also been reported earlier by Patel et al. (2009).

Implications for S management in cropping systems

Management practices like efficient irrigation, using manure, retaining or recycling crop residues and slow release S fertiliser can optimize S use efficiency while maximizing plant yield and maintaining S balance in cropping systems including peanut in sandy soil (Blair et al. 1991; Till and Blair 2016).

Farmers in this study applied surface irrigation for peanut frequently, suggesting that water saving irrigation (sprinkler irrigation following minipan) could minimize leaching losses and improve S balance in cropping systems including peanut. Our data in SCCVN indicated that water saving sprinkler irrigation can decrease leaching of S by 53 - 68% as compared to surface irrigation by farmers (Hoang et al. 2019a). Further estimates of SO_4^{-2} leaching would be useful at field or farm level particularly for tropic regions with a high winter rainfall and for soils with a low SO_4^{-2} retention capacity.

Organic amendments such as FYM, composts or biosolids, can be effective sources of sulfur for enhancing crop production and maintain soil S balance in sandy soil. In our study, S concentration in cattle manure was 0.4%, which less than other reports for animal wastes (0.6 - 0.7% S) reported by Kirchmann and Witter (1992). Reddy et al. (2002) indicated that the S mineralized was higher in FYM treated soils (63.5 to 67.3 % of S added) as compared to poultry manure amended soils (60.5 to 62.3 %). Sulfur addition from organics may also decrease losses of sulfate by leaching. By contrast, Lefroy et al. (1994) has shown that straw was an ineffective S source under flooded conditions. The application of straw depresses the redox potential of the soil which can decrease S availability (Bell 2008), and in addition to the reduced mineralization of organic S from straw, may explain the higher grain yields obtained with incorporation of ashed straw.

Crop residue S mineralization is an important process to fulfill plant S needs during the growing season (Singh et al. 2006). Annual application of manure will increase the soil organic S content in the long term, our study results in SCCVN indicated that applied 8 t ha^{-1} of manure with 0.26% S increased soil S, because, manure applications may also increase the potential mineralization rate. Application of manure and rice husk biochar also improved soil S in SCCVN (Do et al. 2017).

Longer term studies are needed to determine whether a residual effect of long-term organic manure application on deep sands enhances the capacity of the system to supply plant-available S (McNeil et al. 2005).

Soils most likely to show a sulfur response are free draining sandy soils with low organic matter content. Since SO_4^{2-} -S is readily leached from the soil there is no point in attempting to raise soil S levels by excessive fertilization. It is generally claimed that SO_4^{2-} - S is mineralized from organic material when the C/S ratio is less than 200 and is immobilized if the C/S ratio is above 400, whereas C/S ratios between 200 and 400 may cause either net mineralization or net immobilization (Barrow 1960). This rule seems to apply across different organic materials such as sludge, animal manure and plant material (Tabatabai and Chae 1991; Musvoto et al. 2000; Reddy et al. 2002; Eriksen and Kristensen 2002). In SSCVN, farmers often applied cattle manure for peanut with low C/S ratio < 200, suggesting that S will mineralize readily. Hence the S supplied in manure is at risk of leaching if crop S uptake does not keep pace with mineralization (Hoang et al. 2015).

While there are several fertilisers available for correcting a S deficiency, for sands under irrigation, emphasis needs to be given to either controlled release fertilisers or to split applications. There is a wide range of S-containing fertiliser materials which has been used or proposed for use under diverse conditions for peanut such as gypsum, elemental S, pyrite and phosphogypsum (Singh et al. 1991; Singh and Chaudry 1995). By contrast, Baboo (2016) and Chien et al. (2009) pointed out that S-coated urea produced minimal amounts of sulfate over the five harvests and could not be considered a viable fertiliser S source. Nitrogen and phosphate fertilisers such as triple superphosphate, mono-ammonium phosphate or di-ammonium phosphate may be modified by incorporating elemental S to become effective and economical sources of fertiliser S (Blair 2015). Benefit of a slow-release S source in high rainfall environments was reported by Degryse et al. (2018) who examined S fertiliser that contained 5% elemental S and 5% SO_4^{2-}-S over two years.

Conclusion

In peanut crops grown on deep sands, S balances were negative at S fertiliser rates < 30 kg S ha^{-1}, but at higher rates of S fertiliser application that produced maximum pod yield (30 - 45 kg S ha^{-1}), three of four sites showed neutral to slightly positive S balance. Hence, the current practice of removing peanut stem and leaf material from fields for animal fodder will lead to depletion of soil S and over time will require higher application of S rates especially as sands have low S reserves. Management practices that help achieving S balance at the S rates needed for optimum yield include more efficient irrigation to prevent S leaching and recycling of manures from animals and peanut crop residues to fields. Biomass removal from fields for use as cattle feed adds value to the farming system in SCC VN, however, is appears to be the main factor causing negative S balance under irrigated peanut on the deep sands.

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Table 1. Effects of S fertilizer rates on partial S balance

S rates (kg S ha^{-1})	S inputs (kg ha^{-1})					S outputs (kg ha^{-1})				Partial S balance (kg ha^{-1})			
	FYM	S fertilizer	Irrigation	Rainfall	Total	Stem and leaf	Pod	Leaching	Total	Remove stem and leaf	Remove pod	Loss by leaching	Remove all residues and leaching
	Cat Hanh commune – Spring 2015												
0	7.4	0	0.04	0.01	7.5^{a}	11.9^{a}	8.4^{a}	15.1^{a}	35.4^{a}	-4.4^{a}	-0.9^{a}	-7.6^{a}	-27.9^{a}
15	7.4	15	0.04	0.01	22.5^{b}	13.5^{ab}	9.7^{b}	17.4^{b}	40.6^{b}	9.0^{b}	12.8^{b}	5.1^{b}	-18.1^{b}
30	7.4	30	0.04	0.01	37.5^{c}	16.8^{b}	10.5^{b}	18.9^{b}	46.2^{c}	20.7^{c}	27.0^{c}	18.6^{c}	-8.7^{c}
45	7.4	45	0.04	0.01	52.5^{d}	18.4^{bc}	12.3^{c}	19.5^{b}	50.2^{d}	34.1^{d}	40.2^{d}	33.0^{d}	2.3^{d}
Source of variance													
S rate	-	-	-	-	0.000	0.006	0.035	0.047	0.001	0.000	0.000	0.000	0.000
F test	-	-	-	-	**	**	*	*	**	**	**	**	**
	Cat Hanh commune – Spring 2016												
0	8.6	0	0.04	0.02	8.7^{a}	9.7^{a}	7.5^{a}	6.4^{a}	23.6^{a}	-1^{a}	1.2^{a}	2.3^{a}	-14.9^{a}
15	8.6	15	0.04	0.02	23.7^{b}	12.0^{ab}	8.7^{a}	7.9^{a}	28.6^{ab}	11.7^{b}	15.0^{b}	15.8^{b}	-4.9^{b}
30	8.6	30	0.04	0.02	38.7^{c}	15.0^{ac}	9.5^{a}	10.3^{b}	34.8^{b}	23.7^{c}	29.2^{c}	28.4^{c}	3.9^{c}
45	8.6	45	0.04	0.02	53.7^{d}	19.8^{c}	14.1^{b}	13.2^{b}	47.1^{c}	33.9^{d}	39.6^{d}	40.5^{d}	6.6^{c}
Source of variance													
S rate	-	-	-	-	0.000	0.008	0.024	0.007	0.000	0.000	0.000	0.000	0.000
F test	-	-	-	-	**	**	*	**	**	**	**	**	*
	Cat Hiep commune – Spring 2015												
0	8.0	0	0.03	0.01	8.0^{a}	12.2^{a}	8.8^{a}	11.9^{a}	32.9^{a}	-4.2^{a}	-0.8^{a}	-3.9^{a}	-24.9^{a}
15	8.0	15	0.03	0.01	23.0^{b}	14.7^{a}	11.2^{b}	14.8^{b}	40.7^{b}	8.3^{b}	11.8^{b}	8.2^{b}	-17.7^{ab}
30	8.0	30	0.03	0.01	38.0^{c}	17.3^{b}	12.4^{b}	16.9^{b}	46.6^{bc}	20.7^{c}	25.6^{c}	21.1^{b}	-8.6^{b}
45	8.0	45	0.03	0.01	53.0^{d}	19.2^{b}	14.2^{b}	20.5^{c}	53.9^{c}	33.8^{d}	38.8^{d}	32.5^{c}	-0.9^{b}
Source of variance													
S rate	-	-	-	-	0.000	0.042	0.000	0.000	0.008	0.005	0.000	0.000	0.017
F test	-	-	-	-	**	*	**	**	**	**	**	**	*
	Cat Hiep commune – Spring 2016												
0	8.7	0	0.04	0.02	8.8^{a}	14.6^{a}	9.5^{a}	8.7^{a}	32.8^{a}	-5.8^{a}	-0.7^{a}	0.1^{a}	-24.0^{a}
15	8.7	15	0.04	0.02	23.8^{b}	18.4^{b}	10.9^{a}	11.2^{ab}	40.5^{b}	5.4^{b}	12.9^{b}	12.6^{b}	-16.7^{b}
30	8.7	30	0.04	0.02	38.8^{c}	20.5^{b}	10.0^{a}	13.5^{b}	44.0^{b}	18.3^{c}	28.8^{c}	25.3^{c}	-5.2^{c}
45	8.7	45	0.04	0.02	53.8^{d}	22.3^{b}	15.5^{b}	16.2^{c}	54.0^{c}	31.5^{d}	38.3^{d}	37.6^{d}	-0.2^{c}
Source of variance													
S rate	-	-	-	-	0.000	0.014	0.016	0.000	0.000	0.000	0.000	0.000	0.008
F test	-	-	-	-	**	*	*	**	**	**	**	**	**

Different letters in a row for each site and year indicate significant Tukey HSD differences between S rates at α = 5%. **, * and ns indicate $p < 0.01$, $p < 0.05$ and $p \geq 0.05$, respectively.

Table 2. Effect of S fertilizer rates on peanut shoot dry matter, yield attributes and yield from 2015 and 2016 crop harvests

S rate (kg S ha^{-1})	Dry matter yield ($t\ ha^{-1}$)		Pod number $plant^{-1}$		100 pod weight (g)		% Shelling		Pod yield ($t\ ha^{-1}$)		Harvest index (%)	
	Spring 2015	Spring 2016	Spring 2015	Spring 2016	Spring 2015	Spring 2016	Spring 2015	Spring 2016	Spring 2015	Spring 2016	Spring 2015	Spring 2016
	Cat Hanh commune											
0	7.05^{b}	6.88^{a}	17.6	12.6^{b}	123.8	123.8	73.2	74.8	3.31	2.67	47.0	38.7
15	7.14^{b}	7.68^{a}	19.8	13.1^{b}	124.1	125.3	74.4	75.0	3.35	2.95	46.9	38.2
30	7.55^{ab}	7.85^{a}	20.3	13.8^{a}	124.2	124.3	74.7	74.5	3.59	3.26	47.6	41.5
45	7.78^{a}	8.07^{b}	20.6	13.9^{a}	124.8	124.5	75.0	73.8	3.65	3.28	47.1	40.4
Source of variance												
S rate	0.01	0.00	0.18	0.00	0.97	0.93	0.07	0.74	0.56	0.11	0.99	0.58
F test	*	**	ns	**	ns	ns	÷	ns	ns	ns	ns	ns
2	*Cat Hiep commune*											
0	7.04^{b}	6.93^{c}	16.9	16.2b	122.2	124.7	78.2	74.4	3.56	3.26^{b}	50.7	47.2
15	7.22^{b}	7.85^{b}	20.1	16.8^{ab}	123.6	124.8	74.3	75.2	3.67	3.53^{ab}	51.0	45.2
30	7.80^{ab}	8.65^{a}	21.5	17.3^{ab}	124.5	124.6	79.1	75.9	3.83	3.84^{a}	49.3	44.5
45	8.12^{a}	8.78^{a}	21.8	18.7^{a}	125.1	124.8	79.3	76.1	3.90	3.86^{a}	48.3	44.0
Source of variance												
S rate	0.01	0.00	0.00	0.04	0.18	0.99	0.60	0.71	0.11	0.00	0.82	0.30
F test	*	**	**	*	ns	ns	ns	ns	*	**	ns	ns

Different letters in a column for each site and year indicate significant Tukey HSD differences between S rates at $\alpha = 5\%$. **, *, ÷ and ns indicate $p < 0.01$, $p < 0.05$, $p<0.10$ and $p > 0.10$, respectively.

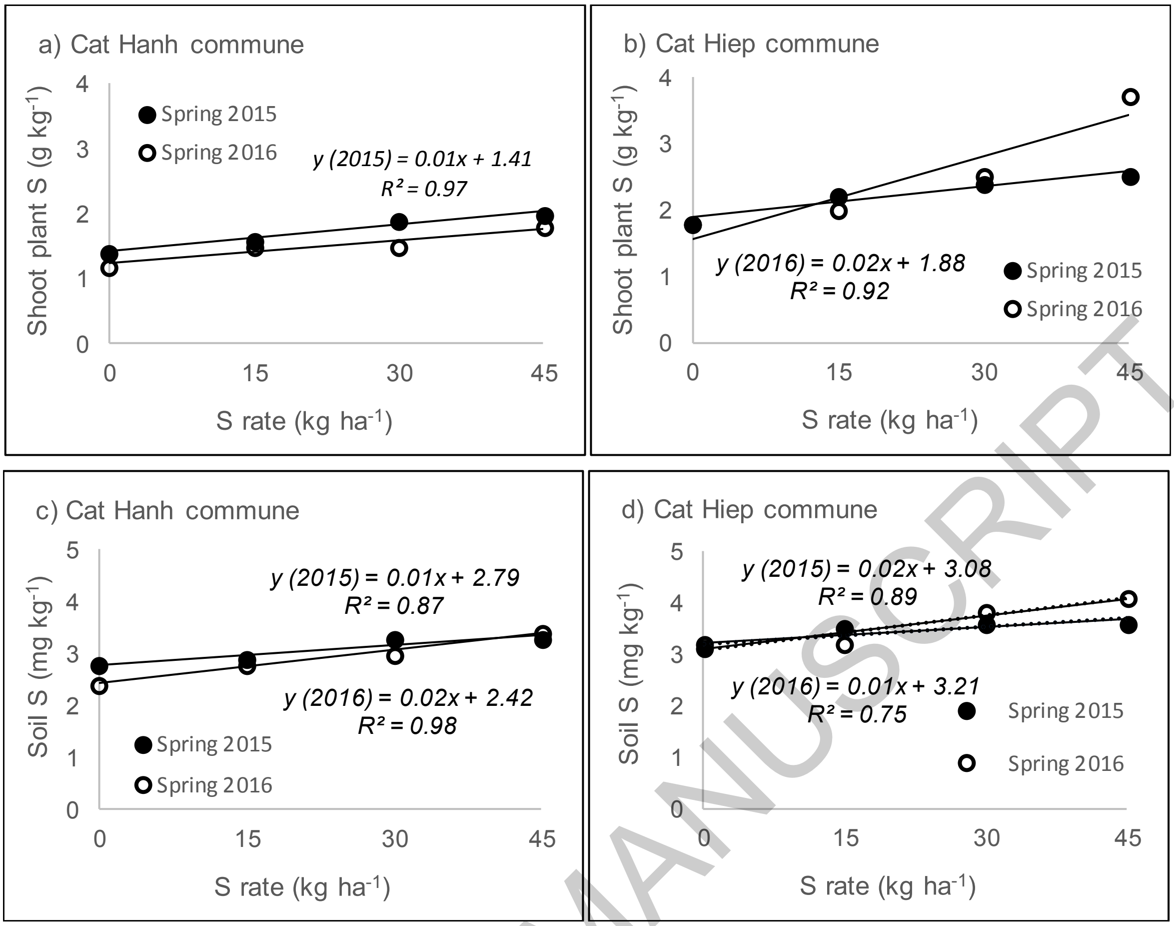

Figure 1. Effects of S fertilizer rates on shoot S concentration and soil S concentration at harvest stage. Values are means of three replicates for each of two sites in consecutive years.

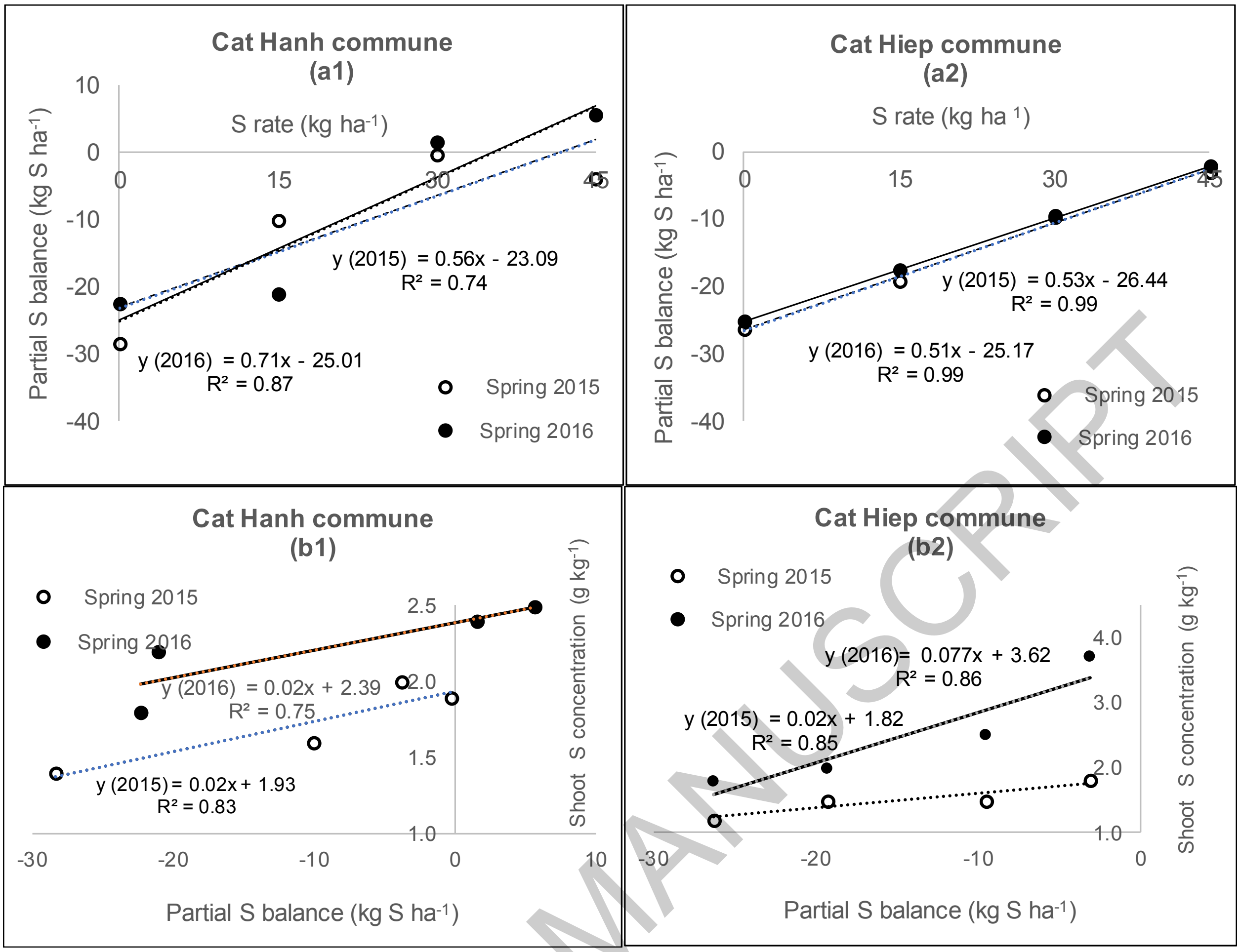

Figure 2. (a1, a2) Relationship between fertilizer S rates and partial S balance in Cat Hanh and Cat Hiep communes in 2015 and 2016; (b1, b2) Relationship between plant S (g kg^{-1}) and partial S balance in Cat Hanh and Cat Hiep communes in 2015 and 2016 growing peanut seasons. Values are means of three replicates for each of two sites in consecutive years.

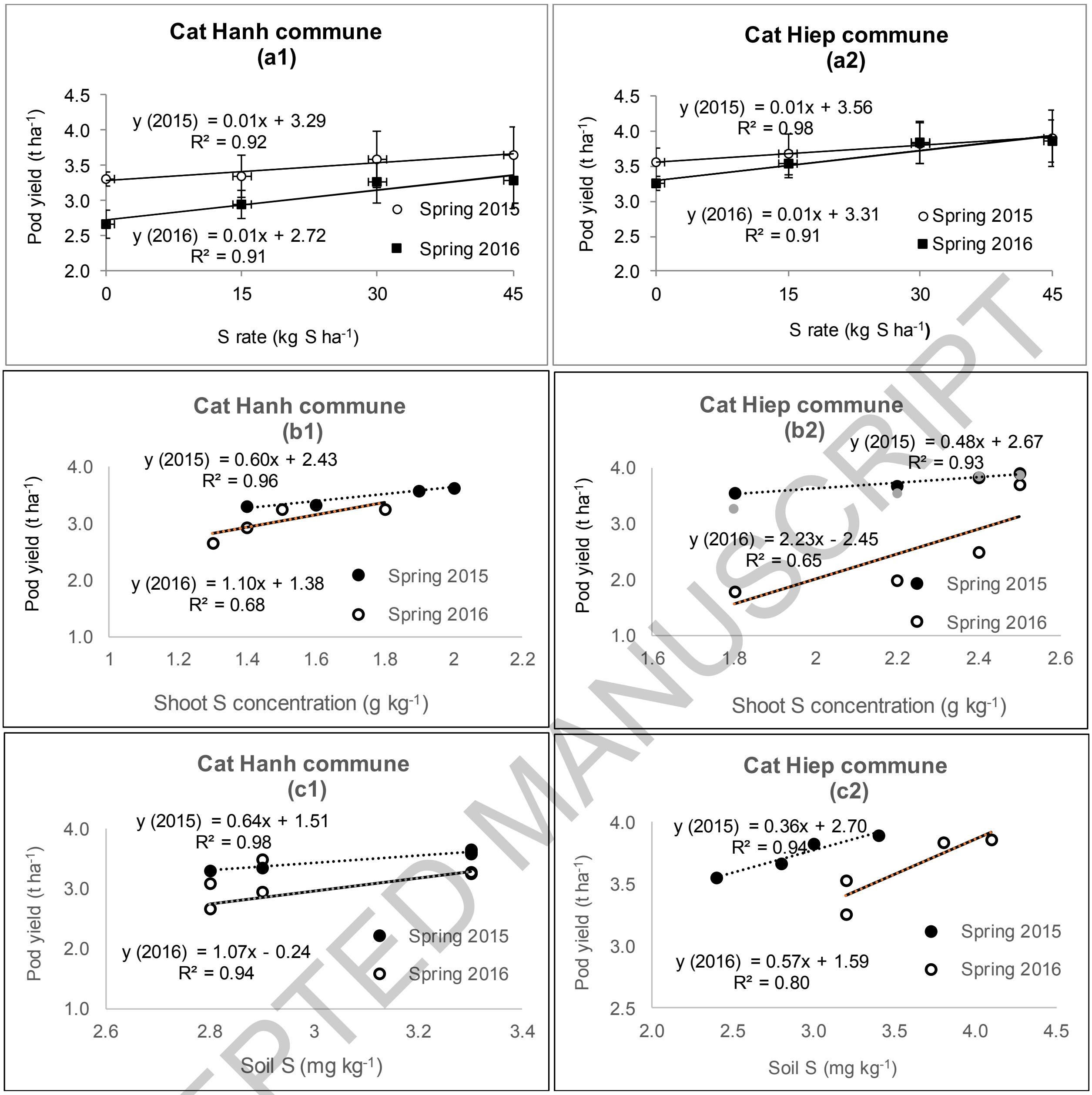

Figure 3. (a1, a2) Relationship between S rates (kg ha^{-1}) and pod yield (t ha^{-1}); (b1, b2) Pod yield (t ha^{-1}) in relation to shoot S content (g kg^{-1}); and (c1, c2) Pod yield (t ha^{-1}) in relation to soil S (mg kg^{-1}). Data derived from Figure 1 and Table 2. Values are means of three replicates for each of two sites in consecutive years.