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Investigating Soil Acidity Associated with Elemental Sulphur Oxidation and Nitrification Process on Soils under Cashew Tree, Southern Tanzania

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Abstract

Cashew nut production in Tanzania is threatened by powdery mildew disease (PMD), which is controlled by large application of elemental sulphur (S) dust. There is a concern that the amount of S reaching the soil has acidifying effect, leading to soil fertility degradation. Soil acidification associated with sulphur application on cashew trees was investigated in two major soils groups: *arenosols* and *ferralsols*, in Southern Tanzania. Soils investigated were both under histories of long-term organic residue removal, additions of cashew, maize and goat farmyard manure (FYM) residues. Sulphur was added to soils at rates of 14.3 and 28.6 $mgSkg^{-1}$ soils equivalent to 36 and 72kg S/ha/a representing quantities reaching soils after dusting trees. Soil pH, SO_4^{2-}-S and NO_3-N were measured at zero time of incubation, and then after every 7 days for 49 days. Soil pH values, amounts of SO_4^{2-}-S, NO_3-N and soil's buffer capacities were used to construct proton budgets of soils. After incubations, a slight acidification in untreated soils was associated with nitrification, while increasing application rates of S increased acidification particularly in soils under the history of organic residue removal, maize and cashew residues additions. S oxidation and nitrification process accounted for Net Proton (NP) generated in soils. The contribution of S oxidation to NP ranged from white nitrification process contribution ranged between 28 and 74%. In a *Luvic arenosol* under the history of goat FYM additions, soil pH depression was small due to high buffer capacity of FYM. The application of potentially alkaline organic residues seems to minimize the risk of soil acidification in these soils, and thus recommended for effective preservation of soil environment.

Keywords: *cashew; sulphur; management; nitrification; proton; oxidation*

Introduction

Soil acidification in tropical ecosystems influences the overall fertility and productivity of many soils (Sanchez & Salinas, 1981; van Breemen *et al.*, 1984; Majule *et al.*, 1997; Sakala, 1998; Majule & Nortcliff, 2001; Fageria & Baligar, 2003). The soil acidification process is defined as the decrease of soil acid neutralising capacity (ANC) resulting from an increase in conjugate acids and a decrease in conjugate bases (van Breemen *et al.*, 1984). The soil acidification process is associated with

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the production or addition of protons in soils through natural processes, or can be triggered by agronomic and other human activities. The consequence of soil acidification is declining food and commercial crops productivity in many agricultural systems.

There are several processes of soil acidification, and among them are the nitrification and oxidation of elemental S in soils (Helyar, 1976; Majule *et al.*, 1997; Sakala, 1998). In Tanzania, cashew (*Anacardium ocidentale*) is the major cash crop to both local farmers and the national economy. The production of cashewnut has been reported to be affected by a fungal disease known as powdery mildew, which is caused by *Oidium anarcadii* Noak (Waller *et al.,* 1992; Martin *et al.,* 1997). Under severe epidemics, cashewnut yields per tree can be reduced to zero. Research conducted on experimental plots for several years concluded that five applications of elemental S dust on cashew trees at the rate of 1.25 kg S per tree/season can reduce the disease and increase nut yield from 1.4 to 11.6 kg/tree/season (Martin *et al.,* 1997). However, Smith *et al.* (1995) explained that the efficiency of elemental sulphur dusting is very low because only less than 20% of the amount dusted is deposited on trees.

The use of elemental S dust is environmentally unsustainable in the sense that it acidifies soils and detrimentally alters the soil properties (Majule *et al.,* 1997). When the amount of proton was calculated in soils incubated with S equivalent to the field application, the elemental sulphur oxidation process accounted for only 1/3 of the net protons generated (Nortcliff & Wong, 1995; Majule *et al.,* 1997). This leads to a speculation that in soils under cashew fields where dusting of elemental S is taking place, other processes, particularly nitrification, accelerate soil acidification. In soils, the nitrification process produces $2H^+$ when NH_4^+ is being converted to NO_3^-, however, $1H^+$ is used up to convert NH_3 to NH_4^+ or $1H^+$ can be neutralised by a base generated in the soil due to the uptake of NO_3^- by plants (Reuss & Johnson, 1986). When a nitrate ion is leached together with other cations, the net charge per mole leached is H^+ and this causes soil acidification. Also, when S is converted to SO_4^{2-}, $2H^+$ are produced. There is limited literature which suggests that elemental S tends to stimulate the nitrification process (Cifuentes and Lindemann, 1993; Cowell and Schoenau, 1995).

In the southern cashew growing areas of Tanzania, a wide range of organic residue management practices affect the fertility of soils exist (Majule, 1999; Majule, 2001; Majule & Nortcliff, 2001). The main objective of this study was to investigate, through incubation experiments, contributions to net protons of elemental S oxidation and nitrification processes. Two soils from southern Tanzania, a *Rhodic Ferralsol* and a *Luvic Arenosol,* each with four histories of organic residue management practices were used.

The Study Area

The Southern coastal areas of Tanzania mainland comprises of Mtwara and Lindi Regions. The area is divided into two major agroecological zones (AEZ) C2 and E5 (De Pauw, 1984). AEZ C2 is found along the east southern cost of Tanzania and is dominated with sand soils (*Arenosols*), while AEZ E5 is found in the inner southern part of Tanzania and is dominated by *Ferralitic* soils. Climatic conditions in Mtwara and Lindi regions are influenced by two major airstreams, the southeast trade winds in mid year, and the northeast trade winds during the turn of the year. There is little seasonal variation in temperatures, with the average mean temperature being 24.3°C in the coolest month (August), and 27.5°C in the hottest month (December). The mean maximum temperature is 30.5°C, and the mean minimum 21.7°C. The rainfall pattern in the southern zone is unimodal but often has a seasonal interruption. Approximately 85% of precipitation falls between December and April; these are defined as 'wet' months on the basis of a minimum of 50mm precipitation. Average annual precipitation for both regions varies between 810mm and 1090mm.

The soils are formed in terrestrial Karoo, Cretaceous and Neogene deposits that are invariably deep and lack surface stone. The soils are impoverished and the surface organic matter is the only nutritive resource. Two dominant soils found in selected sites for research are *Luvic Arenosol* in AEZ C2 and *Rhodic Ferralsol* in AEZ E5. Soils are characteristically very low in available nutrients, poor water holding capacity, and are very sensitive to water erosion. Similar soils found near the study areas are described in details elsewhere (Bennett *et al.,* 1979; 1995; Majule, 1999; Majule, 2001).

Materials and Methods

Soil Properties

A total of 10 composite soil samples were collected from *Luvic Arenosol* and *Rhodic Ferralsol* occurring in the two common Agro-Ecological Zones in Tanzania termed as C2 and E5. Soil samples were collected at a depth of 0-30cm from 5 farmers fields each with histories of organic residue removal; additions of cashew residue; additions of maize residue and additions of goat FYM residue on both soil types. Soil samples were air-dried, sieved to pass a 2mm and analysed for soil pH, organic carbon, total nitrogen, total sulphur, and buffer capacity. Soil pH was determined in distilled water of 1M KCl by glass electrode of a pH meter using 1:2.5 soil: solution (Rowell, 1994). Total carbon and S were determined in the LECO SC-44 analyser, and total nitrogen by mass spectrometry. Acid buffer capacity of soils was determined by the buffer curve method described by Rowell (1994), and adapted by Sakala (1998), Nkhalamba (1999) and Majule (1999). Ten grams of each soil sample was placed in a 150ml-capped plastic bottles, and 23ml of 0.1M KCl was added. The volumes of 0, 0.5, 1.0, 1.5 and 2.0ml of 0.1M HCl, which is equivalent to the addition of 0, 5, 10, 15 and 20mmol H^+ kg^{-1} were then added to pairs of bottles and then made to 25ml with the addition of 0.1M KCl solution. Mixtures were then shaken in a shaking machine for 24 hours before measuring pH. Average buffer capacities of soils were determined from buffer curves as $slope^{-1}$.

Incubation Experiment

To determine the effect of elemental S additions, 200g of soil samples from the sites with histories of organic residue removal, additions of cashew, maize and goat FYM residues were weighed into each of 72 plastic bags (8 soil samples × 3 S regimes × 3 replications). Before treatment application, a soil/sulphur mixture was first prepared by mixing thorough 0.286g of 99% pure elemental S with 10g of soil in 20ml capped glass bottles. The mixture, therefore, contained 0.0286g S/g soil and the amount of 0.1 and 0.2g of soil/sulphur mixture added in three replicates to 200g soil in bags were equivalent to field applications of 36 and 72kg S/ha/a respectively by assuming that the soil contains 2500 t/ha to a depth of 20cm. The untreated soils that received no elemental S and were used as controls. After treatment application, ultra pure water were added to each bag to maintain soil moisture level near to 50% of field capacity, and then mixed thoroughly (see Sakala, 1998; Nkhallamba, 1998). Before incubating soils in plastic bags for 49 days at constant temperature ($30\pm1°C$) in a room, 10g of untreated and treated soils were taken into 100ml polystyrene capped bottle, and then 25ml of IM KCl was added. Mixtures were then shaken for about 30 minutes and then soil pH's were measured in the slurry. After pH determinations, slurries were then shaken on an end - over shaker for a further 90 minutes and then filtered by using GF/A filter paper prior to the determination of NO_3-N. Ten grams from each bag was sampled for SO_4^{2-}-S determination. SO_4^{2-}-S in soils was extracted by using 0.01 M $CaH_4(PO_4)_2.H_2O$ solution following a modified turbidimetric method (Page, 1982). Data collected before incubation will be referred to as zero time incubation. Moist soils in bags were then incubated for the period of 49 days and analysis were repeated at 7 days intervals. The increase in NO_3^--N and SO_4^{2-}-S in soils during incubation was used to calculate the amount of proton produced by the oxidation of elemental S (A) and as a result of nitrification (B). In these calculations, ΔNO_3^- was considered to give 1 mole of H^+ and the conversion of S to SO_4^{2-} was considered to give to 2 moles H^+.

Given that;

$$\text{BC (mmol H}^+\text{ kg}^{-1}\text{ pH}^{-1}) \times \Delta pH = \text{NP (mmol H}^+\text{ kg}^{-1})$$

Where BC is a given buffer capacity of soil, ΔpH is the measured change in pH, NP (net protons) is the calculated amount of protons that would caused this change in pH. A + B gives the total protons contributed by both nitrification and elemental S oxidation processes. 100A/NP and 100B/NP are percentages of the net protons contributed separately by the nitrification and elemental sulphur oxidation processes respectively. NP – (A+B) gave a value termed the proton budget. (A+B) – NP indicates proton excess (+) or proton deficit (-). Effective buffer capacity (EBC) was calculated as ratio of the sum of protons generated by elemental S oxidation (A), nitrification process (B) and mineralization of organic S (C) to the observed soil pH depression. Mineralization of organic S was considered to be important in the construction of proton budget, particularly in soils under the history of goat FYM additions because these soils contained a considerable amount of organic sulphur that could affect the proton budget during S mineralization. The mineralization of organic S also produces 2H+, and this is measured in soils untreated with elemental S.

Results and Discussion

Selected Chemical Soil properties

The chemical properties of the studied *Luvic Arenosol* and *Rhodic Ferralsol* indicate a strong variability under the different management practices (Table 1).

Table 1: Selected chemical properties of *Luvic Arenosol* and *Rhodic Ferralsol* under four different histories of organic residue management practices.

	pH (1:2.5) H_2O	N	OM %	SO_4^{2-}–S mg/kg	Buffer capacity mol H^+kg^{-1} pH^{-1})
a) Luvic Arenosol					
Organic residue removed	5.33	0.057	1.28	4.74	8.80
Cashew residue addition	6.17	0.058	1.55	5.06	10.64
Maize residue addition	5.42	0.061	1.57	4.93	9.54
Goat FYM addition	7.72	0.074	1.80	10.67	23.36
b) Rhodic Ferralsol					
Organic residue removed	5.13	0.045	1.09	4.77	12.11
Cashew residue addition	5.27	0.088	2.25	5.14	13.97
Maize residue addition	5.81	0.069	1.54	8.40	12.44
Goat FYM addition	6.29	0.165	3.38	10.66	17.99

Soil pH (Table 1) in the *Luvic Arenosol* ranged from 5.33 to 7.72 in the sample under the history of organic residue removal and in the sample to which goat FYM had been added respectively. In the *Rhodic Ferralsol*, pH followed a similar trend and ranged from 5.13 (organic residue removal) to 6.29 (goat FYM additions). Total N% and OM% contents also differed in soils depending on the history of organic residue management practices imposed. The amount of available $SO_4{}^{2-}$-S in both soils also seems to be affected by management practices (Table 1).

Acid buffer capacities in the *Luvic Arenosol* ranged from 8.80 mmol H+ kg-1 pH-1 in the sample with a history of organic residue removal to 23.36 mmol H+ kg-1 pH-1 in the sample to which goat FYM residue had been added (Table 1). There were also small increases in buffer capacities in samples with histories of maize and cashew residues additions as compared to the sample under the history organic residue removal. In the *Rhodic Ferralsol* buffer capacities ranged between 12.11 mmol H+ kg-1 pH-1 in samples with a history of organic residues removal, and 17.99 mmol H+ kg-1 pH-1 in a soil with a history of goat FYM addition. These results showed that the *Rhodic Ferralsol* was slightly more highly buffered than the *Luvic Arenosol*. In addition, there was a marked increases in buffer capacities of both soils under the history of goat FYM additions, which suggests that buffer capacities of soils under cashew is influenced by the management of organic residues.

The oxidation of added sulphur in the Luvic Arenosol and its effect on soil pH

Two kind of soil pH changes were distinguished in most soils after incubations: a slight decline in soil pH in untreated soils, and a marked decline in elemental S treated soils. In the soil with a history of organic residue removal, soil pH at zero time (Figure 1a) was ~4.8. At day 7 of incubation, soil pH values in both untreated and treated samples were almost similar (pH~4.7). After 7 days of incubation, soil pH values were lower in samples treated with S as compared to the untreated soil. For example, at day 49, soil pH values ranged between 4.47 in a sample treated with an amount equivalent to 72 kg S/ha/a, and 4.67 in the untreated sample. An increase in the amount of extractable SO4-2-S in treated soils (Figure 1a) suggests soil acidification due to elemental S oxidation process by micro-organisms (Nor & Tabatabai, 1977; Watkinson & Bolan, 1997).

In the soil under the history of cashew residue (Figures 2b) a similar pattern of changes in soil pH was observed. Soil pH declined by 0.16, 0.21 and 0.28 pH units in untreated and samples treated with equivalent of 36 and 72 kgS/ha respectively after 49 days of incubation. The increase in the amount of elemental S converted to sulphate was associated with a decline in soil pH. After 28 days of the incubation almost the entire elemental S added was completely oxidised. In the soil under the history of maize residue additions (Figure 1c), soil pH declined by 0.11, 0.21 and 0.29 pH units in untreated soil and soils treated with equivalent of 36 and 72 kgS/ha

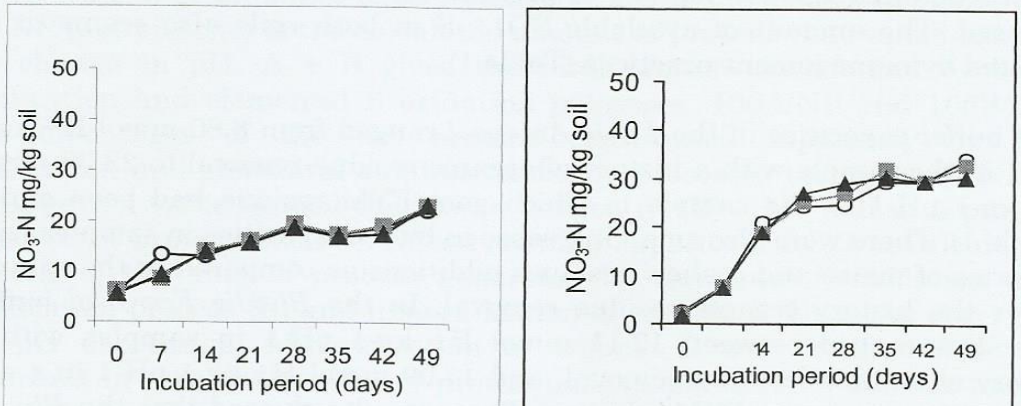

Figure 3a. Organic residue removal

Figure 3b. cashew residue additions.

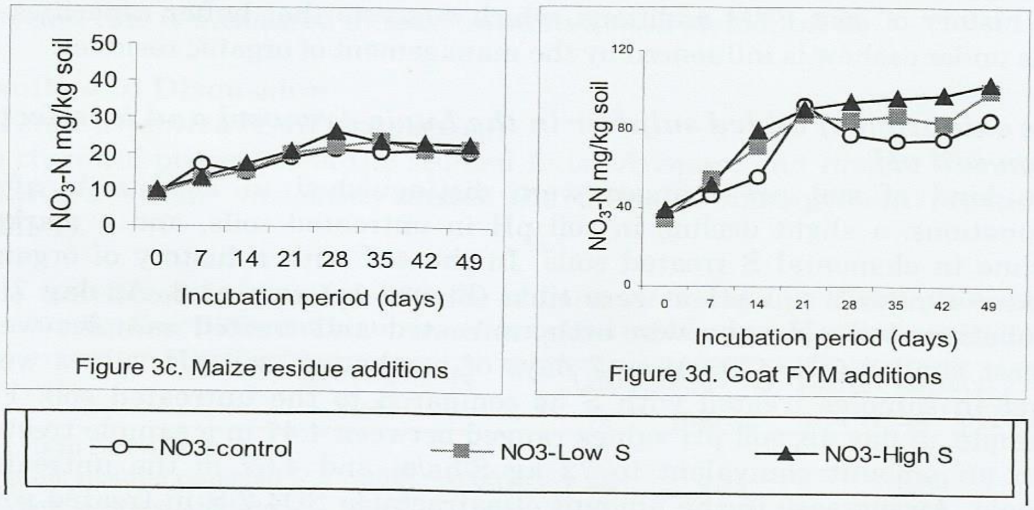

Figure 1a-1d: ***Impacts of incubating low and high rates of elemental S on soil pH in*** Luvic Arenosol

respectively after the incubation period. In the soil under the history of goat FYM addition (Figure 1d) there was no significant pH reduction probably due to high pH buffering. In summary it can be concluded that after the incubation period, minor soil pH depressions were observed in all untreated soils under different histories of organic residue management practices with the exception of the soil under the history of goat FYM additions. In similar soils treated with different levels of elemental S, depressions in soil pH increased with an increase in the application rates.

The oxidation of added sulphur in Rhodic Ferralsol and its effect on soil pH

The initial soil pH of untreated and treated soils under the histories of organic residue removal, additions of cashew residues, additions of maize residues (Figure 2a-2d) were broadly similar (pH 4.33 - 4.36). However soil pH value of the soil under the history of goat FYM addition (Figure 2d) was slightly higher but less than of *Luvic Arenosol* under the history of goat FYM additions Generally soil pH values for the *Rhodic Ferralsol* soils were lower than those of the *Luvic Arenosol* (Figure 2a-d).

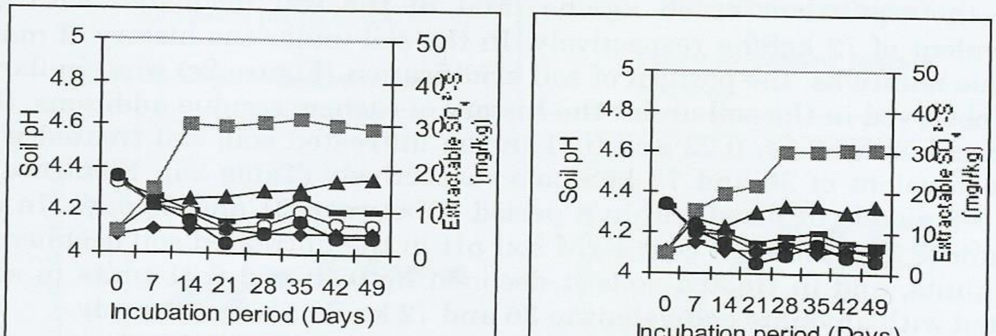

Figure 2a. Organic residue removed

Figure 2b. cashew residue addition.

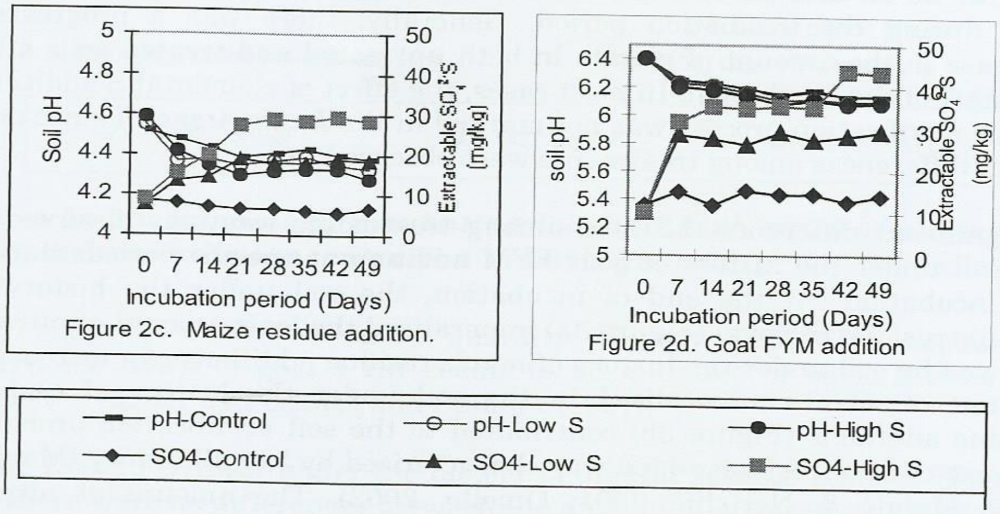

Figure 2c. Maize residue addition.

Figure 2d. Goat FYM addition

Figure 2a-2d. ***Impacts of incubating low and high rates of elemental S on soil pH in*** Rhodic Ferralsol

The pattern of soil acidification and elemental S oxidation were however broadly similar to those observed for similar treatments in the *Luvic Arenosol* soils. In most cases, data suggests that for the major soils founds in cashew areas in southern zone, a complete oxidation of elemental S can be attained within a period of 21 days. Depressions in pH values of the soil under the history of organic residue removal were 0.10, 0.20 and 0.28 pH units in the untreated, soils treated with the equivalent of 36 kg S/ha, and in the soil treated with the equivalent of 72 kg S/ha respectively (Figure 2a). In the soil under the history of cashew residue additions (Figure 2b), soil pH declined by 0.20, 0.25 and by 0.30 pH units in the control, in the soil treated with the equivalent of 36 kgS/ha, and in the soil incubated with the equivalent of 72 kgS/ha respectively. In the soil under the history of maize residue additions, the pattern of soil acidification (Figure 2c) was similar to that observed in the soil under the history of cashew residue additions. Soil pH declined by 0.14, 0.22 and 0.31 in the untreated soil, soil treated with the equivalent of 36 and 72 kgS/ha/a respectively (Table 2b). Elemental S was completely oxidised within a period of between 21 and 28 days. In the soil under the history of goat FYM soil pH in the untreated soil declined by 0.26 units, and in treated soils it declined by 0.30 and 0.31 units in soils treated with amounts equivalent to 36 and 72 kg S/ha/a respectively.

Nitrogen Transformation in Soils

Figures 3a-3d and 4a-4d indicate nitrification process in the two studied soils during the incubation period. Generally, there was a progressive increase in the amount of nitrate in both untreated and treated soils after the start of the incubation. In most cases, the effect of elemental S additions on the nitrification process was not marked in the *Luvic Arenosol* since only minor differences among treatments were observed.

A significant difference ($LSD_{0.05}$) among treatments was only observed in the soil under the history of goat FYM addition at specific periods during the incubation. At the end of incubation, the soil under the history of organic residue removal (Figure 3a) mineralised the least amount of nitrate, followed by soil under the history of maize residue additions. An increasing amount of nitrate mineralised in the soil under the history of cashew residue additions (Figure 3b) contributed to the soil acidification probably because cashew residue added was characterized by low alkalinity (Majule, 1999; Majule & Nortcliff, 2001; Omollo, 2002). The amount of nitrate accumulated in the soil under the history of goat FYM was the largest (Figure 3d) after incubating soils for 28 days. The accumulation of nitrate in the soil under the history of goat FYM additions without causing a marked soil acidification suggests that farmers can improve the buffer capacity of

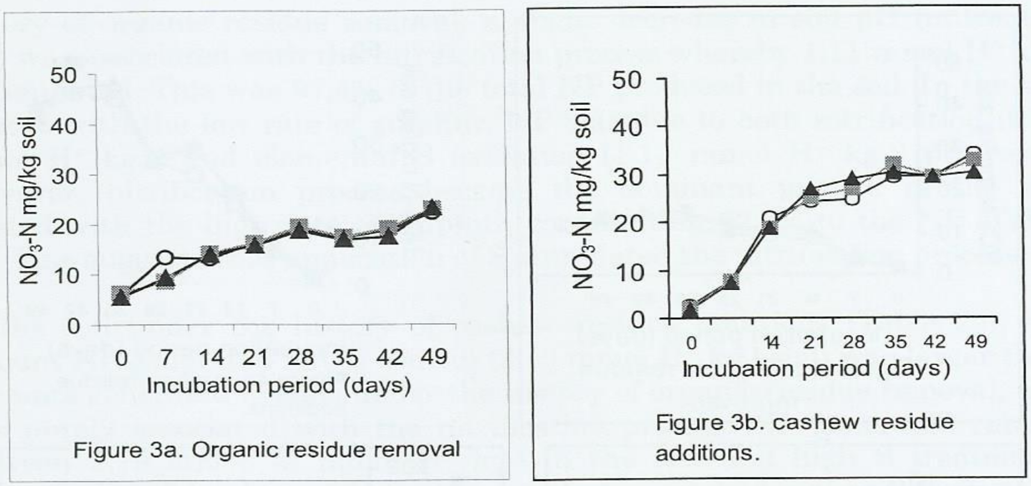

Figure 3a. Organic residue removal

Figure 3b. cashew residue additions.

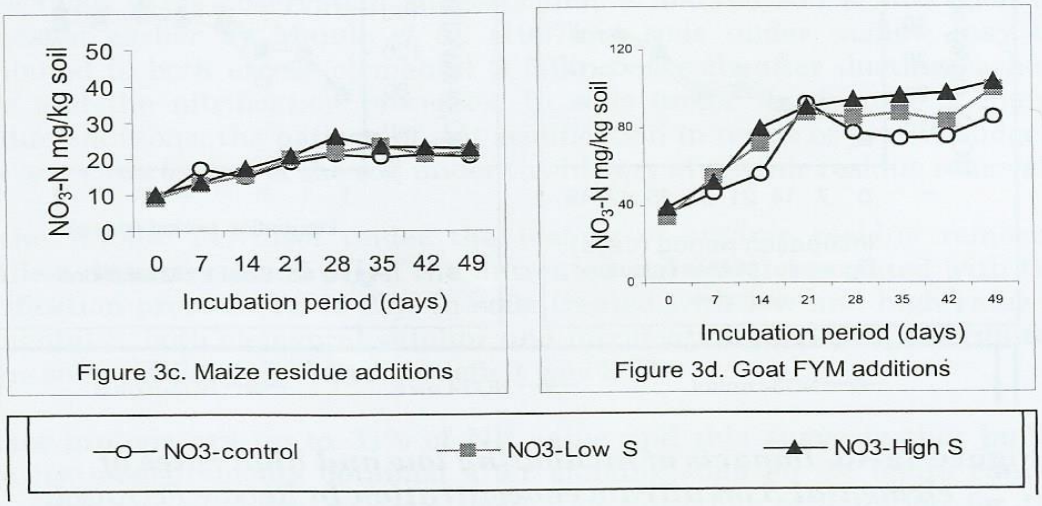

Figure 3c. Maize residue additions

Figure 3d. Goat FYM additions

Figure 3a-3d. ***Impacts of incubating low and high rates of elemental S on nitrate concentration in*** Luvic Arenosol

their soils by adding a small quantity of goat FYM. The microbial breakdown down of goat FYM seems to be a source of basic cations as suggested earlier by Pocknee and Sumner (1997).

In the *Rodic Ferralsol* under the history of organic residue removal (Figure 4a), there were no differences between the amount of nitrate accumulated in the untreated soil and in soils treated with both rates of elemental S. In soils under histories of cashew residue management (Figure 4b) the amount of nitrate mineralised was slightly higher as compared with the amounts mineralised in the soil under the history of organic residue removal.

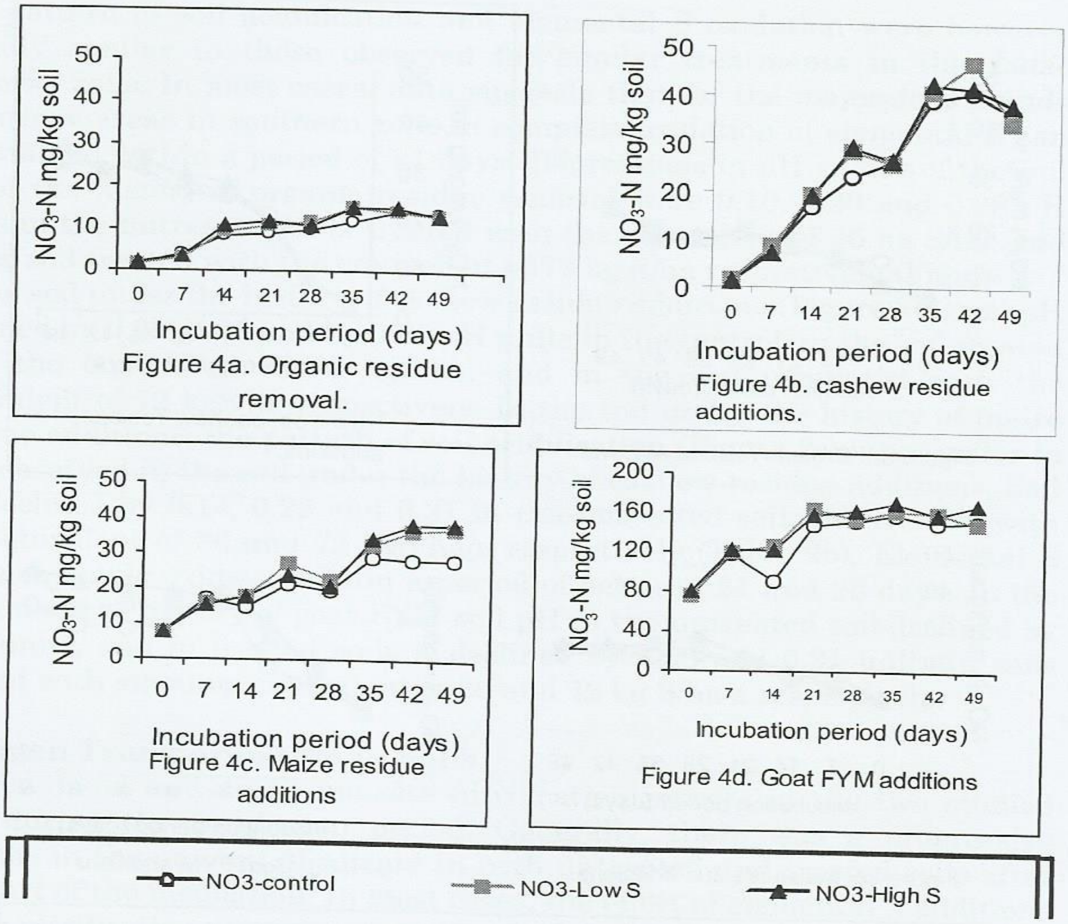

Figure 4a. Organic residue removal.

Figure 4b. cashew residue additions.

Figure 4c. Maize residue additions

Figure 4d. Goat FYM additions

Figure 4a-4d. ***Impacts of incubating low and high rates of elemental S on nitrate concentration in*** *Rhodic Ferralsol.*

The amount of nitrate mineralised in both untreated and treated soils under the history of maize residue additions (Figure 4c) was similar to amounts accumulated in the soil under the history of organic residue removal. The soil under the history of goat FYM additions (Figure 4d) mineralised the largest amount of nitrogen probably due to the presence of residual organic N. Generally, in the soil under the history of goat FYM additions, the amount of nitrate accumulated was large in soils amended with elemental S.

Contribution to Net Proton (NP) by Nitrification and Sulphur Oxidation

The relationship between pH changes, buffer capacities of soils, amounts of S and nitrate accumulated in the two soils can be estimated by a summary of proton budgets of the two soils (Table 2b). In the *Luvic Arenosol* under the history of organic residue removal, a slight decrease in soil pH (untreated soil) was associated with the nitrification process whereby 1.11 mmol H^+ kg^{-1} accumulated. This was 97.4% of the total NP produced in the soil. In the soil treated with the low rate of sulphur, NP was due to both nitrification (0.81 mmol H^+ kg^{-1}) and elemental S oxidation (1.14 mmol H^+ kg^{-1}) processes. However, nitrification process became the dominant process in the soil treated with the high rate of sulphur, contributing 62.3% to the NP (Table 2a). This suggests that application of S stimulated the nitrification process.

In the soil under the history of cashew residue additions (Table 2a), the amount NP generated in the control (2.13 mmol H^+ kg^{-1} soil) was larger than amounts generated in soils under the history of organic residue removal, and was purely associated with the nitrification process. NP generated ranged between 2.79 and 3.73 mmol H^+ kg^{-1} in the low and high S treatments respectively. This observation suggests that a marked soil acidification as suggested earlier by Majule *et al.* (1997) in soils under cashew may be attributed to both excess elemental S falling on soils after dusting cashew trees and the nitrification processes. In soils under the history of maize residue additions, the pattern of soil acidification in-terms of proton budgets was very close to that of the soil under the history of organic residue removal.

In the *Rhodic Ferralsol* under the history of organic residue removal, smallest decrease in soil pH of the untreated soil (74%) associated with the nitrification process (Table 2b). In soils treated with low and high rates of elemental S, both elemental sulphur and nitrification processes contributed to the soil acidification. A proton deficit was 2.2%.

Excess protons are up to 31% of NP value and this suggests that buffer capacity measurements obtained after shaking soils for 24 hours cannot give effective value for 49 days incubation. Another explanation for the excess proton observed is the presence of other acid producing reactions apart from nitrification and oxidation of S. Other acid producing reactions include assimilation of cations, reverse weathering of cations and weathering of anionic components (Van Breemen *et al.,* 1984).

In the *Rhodic Ferralsol* the soil under the history of cashew residue additions was similarly markedly acidified by the nitrification process contributing 54.7, 62.9 and 93% in soils treated with high, low rates of S and the untreated soil respectively. This further suggests that the mineralisation of residual cashew leaves contribute to the soil acidification process reported earlier (Majule *et al.,* 1997; Majule and Norticliff, 2001). In the soil under the history of maize residue additions, soil acidification in the untreated soil was associated with the nitrification process. Both elemental S and nitrification processes contributed to the soil acidification in treated soils.

Table 2a: Proton budgets (PB) of *Luvic Arenosol* with 3 known histories of organic residue management practices after incubating soils without or with two levels of elemental sulphur for 49 days.

Management Practice	Sulphur levels	Change in pH (*ΔpH*)	Net Proton (NP) (*BC x ΔpH*) (mmol H^+kg^{-1})	*A* Protons (S-oxid.) (mmol H^+kg^{-1})	*B* Protons (Nitrif.) (mmol H^+kg^{-1})	*A + B* (mmol H^+kg^{-1})	Proton excess (+)/deficit (-) $100\,(1-\frac{A+B}{NP})$	Contribution to NP (%) A/NP	B/NP
Organic Residues Removed	control	0.13	1.14	-	1.11	1.11	2.6	-	97.4
	36 kg/ha	0.23	2.02	0.81	1.14	1.95	3.5	40.1	56.4
	72 kg/ha	0.31	2.73	1.70	1.20	2.90	-6.2	62.3	44.0
Cashew residues addition	control	0.16	2.13	-	2.18	2.18	-2.3	-	102.3
	36 kg/ha	0.21	2.79	0.80	2.06	2.86	-2.5	28.7	73.8
	72 kg/ha	0.28	3.73	1.57	2.04	3.61	3.2	42.1	54.7
Maize residues addition	control	0.11	1.05	-	0.85	0.85	19.1	-	80.9
	36 kg/ha	0.21	2.00	0.92	0.93	1.85	7.5	46.0	46.5
	72 kg/ha	0.29	2.77	1.62	0.93	2.55	7.9	58.5	33.6

Table 2b: Proton budgets (PB) for *Rhodic Ferrasols* with 3 known histories of organic residue management practices after incubating soils without or with two levels elemental sulphur for 49 days

Management Practices	Sulphur levels	Change in pH (*ΔpH*)	Net Proton (NP) (*BC x ΔpH*) (mmol H^+kg^{-1})	*A* Protons (S-oxid.) (mmol H^+kg^{-1})	*B* Protons (Nitrif.) (mmol H^+kg^{-1})	*A + B* (mmol H^+kg^{-1})	Proton excess (+)/deficit (-) $100\,(1-\frac{A+B}{NP})$	Contribution to NP in % *A/NP*	*B/NP*
Organic Residues Removed	control	0.10	1.21	-	0.89	0.89	26.4	-	73.6
	36 kg/ha	0.20	2.42	0.77	0.90	1.67	31.0	31.8	37.2
	72 kg/ha	0.28	3.39	1.51	0.96	2.47	27.2	44.5	28.3
Cashew residues addition	control	0.20	2.79	-	2.40	2.40	14.0	-	92.6
	36 kg/ha	0.25	3.50	0.62	2.20	2.82	19.4	17.7	62.9
	72 kg/ha	0.30	4.20	1.57	2.51	4.08	02.9	37.4	54.7
Maize residues addition	control	0.14	1.74	-	1.44	1.44	17.2	-	82.8
	36 kg/ha	0.22	2.74	0.77	2.03	2.80	-2.2	28.1	74.1
	72 kg/ha	0.31	3.86	1.39	2.17	3.56	07.8	36.0	56.2

Table 3: Proton budgets (PB) of *Luvic Arenosol* soil and *Rhodic Ferralsol* soil with histories of goat FYM residue additions after incubating without or with two levels of elemental sulphur for 49 days

Soil type	Sulphur levels	Change in soil pH (-ΔpH)	*A* Element S-oxid. (mmol H^+kg^{-1})	*B* Nitrification (mmol H^+kg^{-1})	*C* Organic S miner. (mmol H^+kg^{-1})	$D = (A+B+C)$ in mmol H^+kg^{-1}	$EBC = D/\Delta pH$ mmol H^+kg^{-1} pH^{-1}	Proton (%) neutralised *100 (D -NP)/D*
Luvic Arenosol	control	0.02	-	2.81	1.08	3.89	195	88
	36 kg/ha	0.06	0.90	3.54	1.16	5.60	93	75
	72 kg/ha	0.14	1.80	4.20	1.26	7.26	52	75
Rhodic Ferralsol	control	0.26	-	5.25	0.22	5.47	21	14
	36 kg/ha	0.30	0.90	5.89	0.28	7.07	24	24
	72 kg/ha	0.31	1.80	5.52	0.32	7.64	25	27

Note: Calculations to obtain the amount of protons neutralised was based on the fact that all of elemental S added was assumed to be completely oxidised and again there was oxidation of organic sulphur contributed to soil acidity.

Proton Budgets in Soils under the History of FYM Additions

Under the history of goat FYM additions, lower soil pH depressions observed in both soils suggests that protons entering into the reactions are not effective in a 24 hours measure of buffer capacity. Table 3 presents the amount of protons contributed by the oxidation of organic sulphur from the residue goat FYM. Results indicate that in the *Luvic Arenosol,* EBC decreased with increased S application rates, which further suggests the acidifying tendency of S. In this case, between 75 and 88% of protons generated was neutralised in the treated and untreated soil respectively (Table 3). Application of S on trees that growth under such soil is therefore not likely to have severe environmental impacts on soils (increased levels of exchangeable Al) because a considerable amount of protons is neutralized.

In the *Rhodic Ferralsol*, EBC values were lower than that of *Luvic Arenosol* and relatively small amounts of protons were neutralised ranging from 14% to 27% in the untreated and the soil treated with the amount equivalent to 72 kg S/ha/a. Possible explanations for proton neutralisation process are (1) high initial soil pH suggests larger concentration of base or due to the presence of NH_4OH from residual goat FYM; (2) activation of non-soluble alkalinity present in added residue during the mineralisation process, for example, microbial breakdown of Ca oxalate organic molecule indicated below (Pocknee & Sumner, 1997):

$$CaC_2O_4 + 1/2O_2 \rightarrow CaCO_3 + CO_2$$

(3) Finally, it was probably due to the association of protons with different organic anion molecules present in residual goat FYM (Ritchie & Dolling, 1985).

Conclusions

This study confirms the soil acidification process associated with the dusting of elemental S in cashew growing areas of southern Tanzania. In the absence of dusting activity, a slight soil acidification is associated with the nitrification, and this depends on the type of residue added. Soils with a low buffering capacity, particularly those under the history of organic residue removal and low clay content, are acidified mostly. The amount of net protons accumulated in soils dusted with elemental S was between 28.3 and 74.1% accounted for varying degrees the soil nitrification process depending on the initial N contents. In soils under the history of goat FYM additions, lower soil pH depressions observed suggests that protons entering into the reactions are not effective in a 24 hours measure of buffer capacity. Generally, the additions of potentially alkaline organic residue particularly goat FYM in soils can prevent a rapid soil acidification process after dusting trees with S. However, while alternative control measurers are being investigated, the amount of S reaching the soil must be minimized.

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