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Land use change from rainforests to oil palm plantations and food gardens in Papua New Guinea: Effects on soil properties and S fractions

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Abstract

Changes in soil sulfur (S) fractions were assessed in oil palm and food garden land use systems developed on forest vegetation in humid tropical areas of Popondetta in northern Province. The study tested a hypothesis that S in food gardens are limiting nutrient factor and are significantly lower than in plantations and forests. Subsistence food gardens are under long-term slash and burn practice of cropping and such practice is expected to accelerate loss of biomass S from the ecosystem. From each land use, surface soil (0–15 cm) samples were characterised and further pseudo-complete fractionated for S. Conversion of forest to oil palm production decreased ($p < 0.001$) soil pH and electrical conductivity values. The reserve S fraction in soil increased significantly ($p < 0.05$) due to oil palm production (~ 28 %) and food gardening activity (~ 54 %). However, plant available SO_4^{2-}-S was below 15 mg kg^{-1} in the food garden soils and foliar samples of sweet potato crop indicating deficiency of plant available S. Soil organic carbon content (OC) was positively and significantly correlated to total S content ($r = 0.533$; $p < 0.001$) among the land use systems. Thus, crop management practices that affect OC status of the soils would potentially affect the S availability in soils. The possible changes in the chemical nature of mineralisable organic S compounds leading to enhanced mineralisation and leaching losses could be the reasons for the deficiency of S in the food garden soils. The results of this study conclude that long-term subsistence food gardening activity enriched top soils with reserve S or total S content at the expense of soluble S fraction. The subsistence cropping practices such as biomass burning in food gardens and reduced fallow periods are apparently threatening food security of oil palm households. Improved soil OC management strategies such as avoiding burning of fallow vegetation, improved fallows, mulching with fallow biomass, use of manures and S containing fertilisers must be promoted to sustain food security in smallholder oil palm system.

Keywords: food garden, land use change, oil palm plantation, organic carbon, reserve sulfur, soil fertility

1 Introduction

Papua New Guinea (PNG) is very diverse with respect to crops grown, cropping systems and their management techniques. Subsistence food production is the most important part of PNG agriculture. It provides most of the food consumed in the country – an estimated 83 % of food energy and 76 % of protein (Bourke & Harwood, 2009). On the other hand, intensive crop and animal production with commercial interests also feature the agricultural scenario. In PNG, land use conversion to subsistence agriculture is one of the major drivers (46 %) of forest cover change while clearing for agricultural plantations contribute to small portion (1 %) of forest cover change (Shearman *et al.*, 2009).

Use of forest land for agricultural production is known to change fertility and biological characters of

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soil, including cycling of nutrients. Changes in soil properties have implications to the maintenance of productivity of new land use systems and subsequent soil management. Effects of land use conversion on stock of soil C, N, physical properties and microbiological activities, besides loss of biodiversity and greenhouse gas emissions are understood (Acin-Carrera *et al.*, 2013; Havaee *et al.*, 2014; Hunke *et al.*, 2015). Except for few studies (Solomon *et al.*, 2001; Wang *et al.*, 2006), there is paucity of information on the changes in S fractions due to land use change in the tropics.

In many South-East Asian countries prominent forest change took place to oil palm (*Elaeis guineensis* Jacq.) plantations. In PNG area planted to oil palm is around 130,000 ha and further expansion of oil palm production is expected at a rate of 3000 ha yr^{-1} (Nelson *et al.*, 2014b). In 2010, oil palm made up 56 % of the total value of PNGs agricultural exports (i.e., ~ US$ 1.5 billion). Oil palm industry in PNG includes a plantation sector and a smallholder sector. Plantation sector is operated by several large milling companies and the smallholders mostly depend on them for inputs and sale of oil palm fruits. The smallholder sector covers around 40 % area planted with oil palm, but produces only around 32 % of the oil palm (Fisher *et al.*, 2012). Thus, the productivity of smallholder oil palm is relatively poor. Conversion of forest vegetation to oil palm reported to maintain soil structure and major nutrients balance in the desirable range despite a decline in pH and exchangeable cations over medium-to long-term (Nelson *et al.*, 2014a).

In the smallholder oil palm blocks of PNG, apart from oil palms, an adjoining parcel of land is allocated to food gardening. Each smallholder typically owns an oil palm block. Food gardens are an integral part of smallholder oil palm blocks for meeting household food requirements and ensuring food security (Koczberski *et al.*, 2012). Food gardens are cultivated by subsistence agricultural activities and involve slashing the natural or fallow vegetation at varying stages of regeneration and burning the dried biomass to grow a variety of food crops. Soils are worked manually to prepare the land for planting food crops (mostly tubers, vegetables and fruits) in complex pattern to establish mixed food crop gardens (Bourke & Harwood, 2009). Finally, the lands are fallowed as crop productivity in gardens declines. Food gardens are periodically subjected to intentional biomass burning after a short-fallow period (1–2 years). Smallholders maintain small parcel of land under food gardens while other portions of food gardens could be under fallow. Fallow periods have progressively shortened from 5–10 years due to limited arable land within the blocks and rapid population growth. Food security of smallholder oil palm producers depends largely on food gardening as estimated contribution of purchased food to the total calories consumed by these smallholders is just 16 % in PNG (Gibson & Rozelle, 1998).

The practice of slashing fallow vegetation and burning dried biomass before food crops causes considerable effects on cycling of nutrients and environment. Burning the biomass results in 38–84 % of the biomass carbon and nitrogen loss, including emission of sulfur (S) as SO_2 with adverse environmental consequences (Guild *et al.*, 2004; McCarty, 2011). Besides, the aerial inputs of S are quite small in pristine tropical regions of the World due to a low industrialisation level (Lara *et al.*, 2001). Thus, improper handling of biomass in subsistence cropping systems over long-term can have potential consequence on soil S concentrations (Jez, 2008) which could include extensive deficiency of S in cropping systems (Rajashekhar Rao *et al.*, 2012). The study was aimed to test the hypothesis that change of forest lands to long-term subsistence food gardening activity would lead to the depletion of total S and available S fractions in the soil. Such decline is observed in food gardens in highlands of PNG due to increased land intensification and nutrient mining linked to rapid population growth (Bourke & Harwood, 2009). We also contemplate that such depletion in S fractions would not occur in oil palm production systems due to absence of biomass burning.

2 Materials and methods

The hypothesis was tested by comparing top soil issues of smallholder food gardens against oil palm plantations, and rainforests. Soil samples were collected from four sites (Isivini, Igora, Sorovi and Puhemo villages) in Popondetta, northern Province of PNG. These sites were located between latitudes 08.721° and 08.797° S, and longitudes between 148.117° and 148.263° E. The elevation of the study sites was 65 to 258 m asl, and the geological structure consisted of basaltic and andesitic volcanic materials, brecciated lava, scoria, agglomerate, fanglomerate, tuff and volcanic ash types of materials. The land forms are mostly well preserved constructional land forms in a flat landscape with Vitrand soils (Soil Survey Staff, 2014) formed by alluvial re-deposition of tephra. The climate is a humid tropical with an annual rainfall of ~ 2380 mm. In these study sites, oil palm blocks were established by clearing primary forests under Land Settlement Schemes or Village Oil Palm Scheme beginning from 1967 (Koczberski *et al.*, 2012). Alienated forest land after clearing was sub-divided into smallholding oil palm blocks (2–4 ha in size) for the primary purpose of oil palm production. Using a semi-structured questionnaire, 25 farmers involved in oil palm production were interviewed about cropping history and management practices and also confirmed that prior to oil palm planting the lands were under natural forest. Selection of farmers within the village was based on the road access and proximity of blocks to forest site. Oil palm blocks were established 18 to 52 years before the sampling and had oil palm trees planted in triangular pattern (125–140 palms ha^{-1}).

Apart from oil palms, these farmers practiced food gardening on an adjoining parcel of land. Diversified crops were grown in the food gardens such as sweet potato (*Ipomoea batatas* (L.) Lam.), taro (*Colocasia esculanta* Schott), Yam (*Dioscorea* sp.), cassava (*Manihot utilissima* Pohl), leafy vegetables such as pumpkins (*Cucurbita pepo* L.), aibika (*Abelmoschus manihot* (L.) Medik.), *Amaranthus* sp., papaya (*Carica papaya* L.), banana (*Musa* sp.), snake bean (*Vigna unguiculata* ssp. *sesquipedalis* [L.] Verdc.), peanut (*Arachis hypogea* L.) and many more. The ratio of food garden area to number of persons ranged from 0.06 ha $person^{-1}$ to 0.71 ha $person^{-1}$ with an average food garden size of 3150 m^2 $person^{-1}$. Sweet potato is the staple crop, providing more than 80 % dietary energy of the households and hence occupied considerable area of the food gardens.

The forest plots utilised for the study consisted of secondary forests, occasionally with stands of tall grass (*Saccharum spontaneum* L.) interspersed with pioneering low-or medium-crowned trees such as *Piper aduncum* L., *Casuarina* sp., *Anisoptera* sp., *Spathodea campanulata* P.Beauv., *Trichospermum* sp., and *Macaranga* sp..

2.1 Soil and plant sampling

In each site, geo-referenced soil samples from three land use systems (natural forest, oil palm and food gardens) were collected in November 2012. The land use systems were 0.1 to 2 km apart within a site, thus, had similar soil characters before different land use practices were imposed. A sampling unit of 5 m × 5 m was identified in the forest patches and food gardens. In each sampling unit 10 soil samples (0–15 cm depth) were collected randomly by a hand auger and pooled. Study was limited to surface samples because highest changes in soil biological and chemical fertility could be expected in the surface layer. The oil palm plantations were sampled from the 'between-zones' (Nelson *et al.*, 2014a). About 10 random soil samples were taken in 'between-zone' stretches and composited. A total of 50 soil samples (4 from forest, 24 from oil palm and 22 from food gardens) were studied. Foliar nutrient diagnosis was carried out by collecting leaf samples of 40–50 day old sweet potato crop (O'Sullivan *et al.*, 1997). Air-dried leaf samples were transported to the laboratory and further oven dried at 80 °C until constant weight.

2.2 Soil-plant analysis and S fractionation

Air-dried soil samples (2 mm sieved) were analysed for chemical properties and sulfur fractions at the Unitech Analytical Services Laboratory, PNG. The soil pH and electrical conductivity were measured with a soil to water ratio of 1 : 5 in a potentiometer and conductivity bridge, respectively (Sparks, 1996). Soil particle size analysis was carried out by hydrometer method. Exchangeable cations were extracted in ammonium acetate at pH 7 (*ibid.*) and analysed for Ca, Mg and K in an ICP-OES (Varian 725ES model). A sub-sample (0.17 mm sieved) was analysed for the soil organic carbon content by Walkley and Black's wet digestion method (*ibid.*). Total soil N content was determined by modified Kjeldahl method (*ibid.*). Sulfate-S was extracted by shaking 20 g soil sample in 100 mL $Ca(H_2PO_4)_2.H_2O$ for 1 h and S content measured by turbidimetric method in a UV-VIS spectrophotometer (Shimadzu UV-1800) at 420 nm (Chesnin & Yien, 1951). For soluble S determination, 10 g soil was shaken with 25 mL of 0.5 N ammonium acetate + 0.25 N acetic acid mixtures for 3 min and filtered through Whatman 42 paper (Bardsley & Lancaster, 1965). Oxidisable S in the extract was estimated turbidimetrically in a UV-VIS spectrophotometer at 420 nm (Chesnin & Yien, 1951). Soluble S fraction includes adsorbed, water soluble and a part of easily oxidisable organic forms of S. For total soil S analysis, 2.5 g soil (0.17-mm sieved) was ignited with $NaHCO_3$ powder in an electric muffle furnace at 500 °C for 3 h. Cooled off sample was then extracted with 25 ml of $NaH_2PO_4.H_2O$ and filtered through Whatman 1 paper. Sulfur content in the extract was analysed by turbidimetric method (Bardsley & Lancaster, 1960; Ribeiro *et al.*, 2001). The difference between total soil S and soluble S was considered as reserve S. Sweet potato leaf samples milled to < 1 mm particle size were analysed for total N, P, K and S contents. The concentration of total P, K, and S were determined in an ICP-OES (Varian 725ES model) after digesting in a mixture of $HClO_4$ and HNO_3. Leaf N content was estimated by micro-Kjeldahl method (Kalra, 1998).

2.3 Statistical Analysis

The data on soil chemical properties and S fractions were tested for normality by Shapiro-Wilk's test and if needed were log transformed prior to statistical analysis. Significant differences between the three land use systems regarding soil properties were determined by ANOVA and LSD tests in Minitab 16 software for windows (McDonald, 2014). Relationships between soil properties and S fractions were examined by calculating Pearson's linear correlation coefficients and simple regression analysis.

3 Results

Land use had significant ($p < 0.05$) effects on pH, electrical conductivity, exchangeable Ca, Mg and K concentrations (Table 1). The pH values of top soils significantly ($p < 0.001$) decreased due to conversion of forests to oil palm plantation. Electrical conductivity values of forest soils significantly ($p < 0.001$) decreased by ~35 % due to oil palm production. Food garden soils showed slight enrichment of the basic cations (exchangeable Ca, Mg and K) whilst, the oil palm soils registered their depletion compared to adjacent forest patches.

Food gardening activities significantly ($p < 0.05$) improved the reserve S concentrations of forest soils (Fig. 1a). The soluble S fraction in food garden soils was significantly ($p < 0.05$) lower than that in oil palm soils. There was no significant effect of land use change on status of total S.

The reserve S fraction accounted for 90.6-94.5 % of the total S among land use systems. Sulfur status and availability of the soils is mostly influenced by soil OC content and elemental ratios of nutrients in the soil organic matter. The OC: total S ratio and OC: reserve S ratio in oil palm soils were remarkably ($p < 0.05$) greater than in food garden soils (Fig 1b). Conversion of forests to oil palm production increased OC: total S ratio (~24 %) and OC: reserve S ratio's (~22 %) even as the conversion to food garden did not impact these ratios.

Table 1: *Physical and chemical properties of the surface (0–0.15 m) soil samples in different land use systems (n=50). Values in brackets indicate standard deviation.*

Soil properties		Natural forest (n=4)	Oil palm (n=24)	Food garden (n=22)	ANOVA p value
pH	Range	6.26–6.40	5.13–6.60	5.61–6.54	
	Mean	6.32 (0.06) ^{a}	5.69 (0.29) ^{b}	6.09 (0.24) ^{a}	0.0001
Electrical conductivity (dS m^{-1})	Range	0.54–0.91	0.22–0.71	0.33–0.79	
	Mean	0.73 (0.20) ^{a}	0.46 (0.14) ^{c}	0.59 (0.12) ^{b}	0.0001
Organic carbon (g kg^{-1})	Range	17.2–29.4	14.7–57.5	20.4–53.9	
	Mean	22.8 (5.13)	35.5 (12.7)	32.5 (9.97)	0.688
Total nitrogen (g kg^{-1})	Range	3.60–6.10	3.10–7.90	3.80–10.9	
	Mean	4.80 (1.28)	5.61 (1.30)	6.24 (1.43)	0.604
Exchangeable Ca (cmol kg^{-1})	Range	1.63–4.95	0.56–5.35	1.65–5.26	
	Mean	3.02 (1.39) ^{ab}	2.27 (1.18) ^{b}	3.23 (0.82) ^{a}	0.008
Exchangeable Mg (cmol kg^{-1})	Range	0.16–0.63	0.07–0.74	0.42–0.80	
	Mean	0.49 (0.22) ^{ab}	0.35 (0.18) ^{b}	0.57 (0.12) ^{a}	0.0001
Exchangeable K (cmol kg^{-1})	Range	0.05–0.18	0.02–0.25	0.06–0.26	
	Mean	0.12 (0.06) ^{ab}	0.09 (0.06) ^{b}	0.16 (0.07) ^{a}	0.003
Clay (g kg^{-1})	Range	92–112	29.2–176	51.8–164	
	Mean	102 (9.52)	76.8 (21.8)	77.3 (24.7)	0.131
Silt (g kg^{-1})	Range	136–224	80–284	80–416	
	Mean	166 (40.6)	141 (61.8)	188 (65.5)	0.341
Sand (g kg^{-1})	Range	664–764	624–824	512–864	
	Mean	732 (46.1)	760 (54.4)	734 (72.0)	0.301

$^{a-c}$ values within the same row with different superscript are significantly different at $p < 0.05$

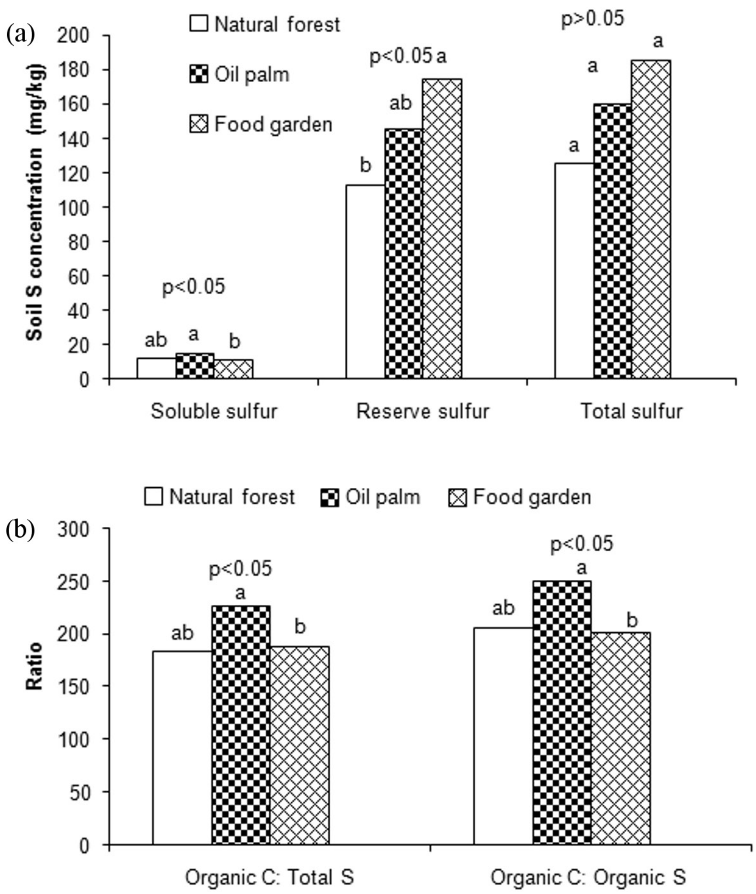

Fig. 1: *(a) Sulfur fractions and (b) Ratio of sulfur fractions in the land use systems. Same lower case letters on a column series are not significantly different ($p > 0.05$).*

Table 2: *Interpretation categories (Hari & Dwivedi, 1994) of plant available* SO_4^{2-}*-S in soils of food gardens and oil palm plantations.*

		Range of soil SO_4^{2-}-S ($mg\,kg^{-1}$)			
		0–10 Deficient	10–15 Low	15–20 Medium	>20 High
Food garden	Frequency (N)	3	19	0	0
	Mean (standard deviation) ($mg\,kg^{-1}$)	5.27 (1.80)	12.3 (1.10)	0	0
	Percent	13.6	86.4	0	0
Oil palm	Frequency (N)	13	5	2	4
	Mean (standard deviation) ($mg\,kg^{-1}$)	5.60 (2.65)	11.2 (0.80)	16.5 (2.1)	22.8 (2.2)
	Percent	54.2	20.8	8.33	16.7

Table 3: *Foliar nutrient status and critical nutrient concentration (O'Sullivan et al., 1997) of sweet potato crop in food gardens of oil palm blocks.*

Nutrient	*Critical nutrient concentration*	*Observed range in leaf samples*	*Mean (SD)*	*% deficient samples*
Nitrogen (%)	4.20	2.48–4.63	3.80 (1.10)	72.7
Phosphorous (%)	0.22	0.23–0.41	0.34 (0.05)	0
Potassium (%)	2.60	2.10–3.16	2.72 (0.36)	27.3
Sulfur (%)	0.34	0.10–0.19	0.15 (0.03)	100

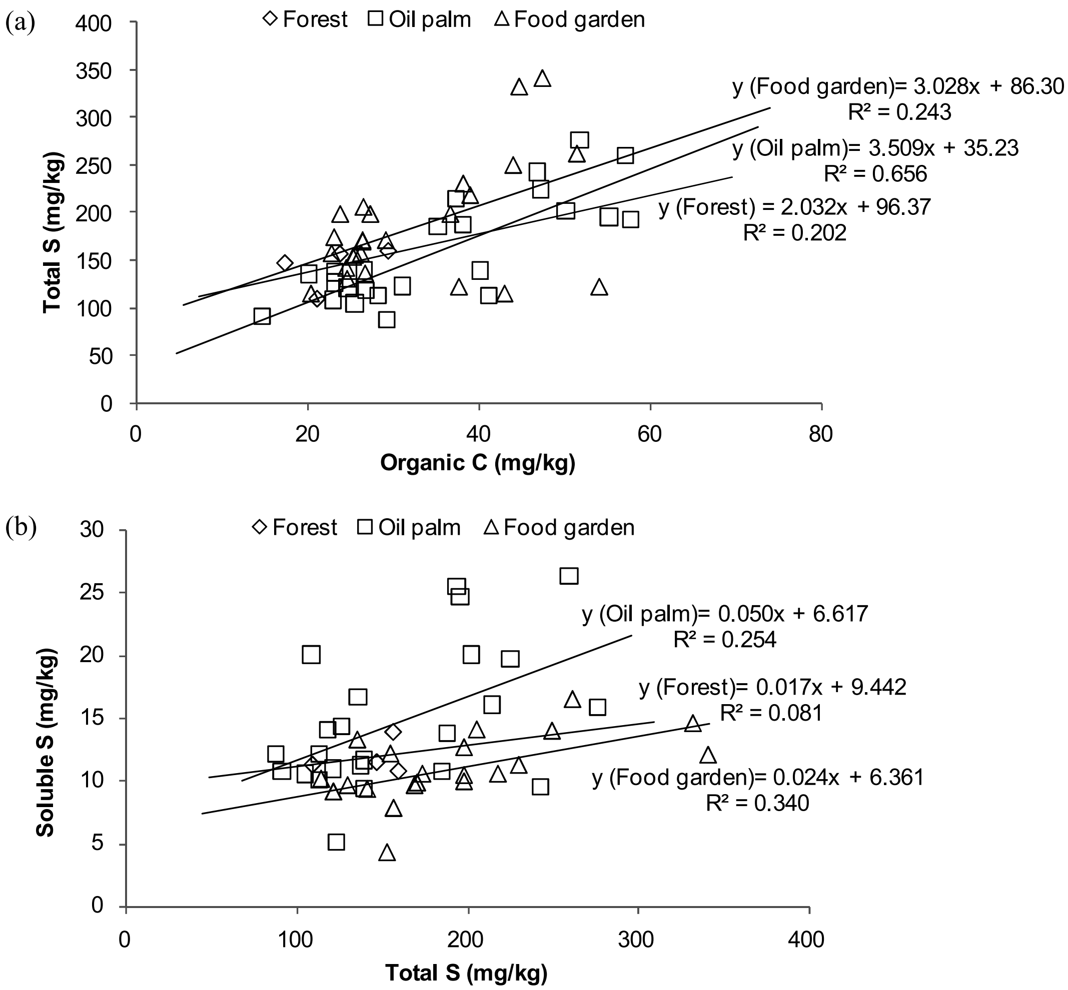

Fig. 2: *(a) Relationship between total S and OC ($y = a + bx$). y-axis is for total S and x-axis for OC; (b) Relationship between soluble S and total S ($y = a + bx$). y-axis is for soluble S and x-axis for total S in different land use systems.*

In food gardens 100 % of the topsoil samples had the SO_4^{2-}-S levels below 15 mg kg^{-1}, thus, categorised into ‘deficient’ and ‘low’ fertility (Table 2). On the contrary, ~ 17 % of the soil samples from oil palm plantations had the SO_4^{2-}-S levels in ‘high’ S fertility category following Hari & Dwivedi (1994). Foliar properties revealed that 100 % of the sweet potato leaf samples had S content below critical nutrient concentration of 0.34 % (Table 3); followed by the deficiency of N (72.7 %) and K (27.3 %) while the P concentration was ‘adequate’ in all foliar samples.

The soil soluble S fraction (plant available S) was positively and significantly correlated (r=0.412; $p < 0.01$) to soil OC content. The soil OC content (r=0.533; $p < 0.001$), was also highly correlated with total S content (r=0.533; $p < 0.001$) (Fig 2a). The soil soluble S content showed a positive relationship with total S, which varied among the land use systems (Fig 2b).

4 Discussion

The results of this study conclude that long-term subsistence food gardening activity enriched top soils with reserve S or total S content at the expense of soluble S fraction. The subsistence cropping practices such as biomass burning in food gardens and reduced fallow periods are apparently threatening food security of oil palm households.

A larger total S pool was expected in oil palm soils than the food garden soils. The repeated burning of fallow vegetation in the food gardens may lead to loss of S from burning biomass. In contrast to the prediction the mean total S content showed an increasing trend in the following order: forest system < oil palm plantations < food gardens. The total S status observed among the three land use soils were comparable to that reported by Itanna (2005) in Ethiopia and slightly greater than that observed by Ribeiro *et al.* (2001) for Oxisols of Brazil. Besides, deep rooted oil palm and forest trees are efficient in pumping-up and recycling S and other nutrients from the lower soil layer to the surface soil (Solomon *et al.*, 2001). However, our results showed enrichment of S in surface soils of food gardens. The reserve S fraction too showed similar pattern of that of total S. The availability of S from total S or reserve S fractions to crops entirely depends on microbial mineralisation which in turn is influenced by the C : S ratio of soils. A net mineralisation is expected in both food gardens and forest soils as in both C : total S ratio is lower than 200 (Blum *et al.*, 2013). The lower mean OC : reserve S ratio of food garden soils indicate greater S mineralisation rates assuming other environmental variables are uniform among the land use systems (Fig. 1b). The biomass charring process in food gardens can create oxidized S species enabling the faster mineralisation of S from the biomass and consequent leaching losses (Blum *et al.*, 2013). Besides, fallow species can contribute nutrients from deeper soil layers through recycling process during fallowing practice of the food gardens (Hartemink, 2003).

In the study there was no significant difference between soluble S status of soils under oil palm and reference forest sites (Fig. 1). Slightly higher S status of oil palm soils could be due to farmers' application of N fertiliser (ammonium sulfate) up to 3 kg palm^{-1} which also contains S (up to 24 % S), mostly in 'between-zone'. Herbaceous, annual crops generate greater biomass and therefore food garden soils had greater soil OC and reserve S status (Aguiar *et al.*, 2014). Although the burning vegetation can cause gaseous emission of C, N and S (Guild *et al.*, 2004), frequent burning promotes an increase of soil OC due to the increased surface crop biomass in the subsequent crop cycle and enhanced OC pool from dead roots (Zhao *et al.*, 2012). Besides, transformations exerted by fire on soil humus, including the accumulation of new particulate C forms bound to S, which are highly resistant to oxidation and biological degradation such as black carbon (González-Pérez *et al.*, 2004).

Except for the pH and electrical conductivity of the soils, other properties did not lend any evidence of chemical degradation due to conversion of forest to either oil palm or food gardens. Oil palm production decreased the pH of forested soils considerably, while, food gardening showed declining electrical conductivity values of soils. Slash and burning of fallow vegetation in Ghana reported to add 1.5–3 t ha^{-1} of Ca and 180 kg ha^{-1} Mg to soil (Schulte & Ruhiyat, 1998). Conversely, a decline in pH, exchangeable Ca, Mg and electrical conductivity values in oil palm could be due to non-agricultural acidification processes such as N-cycling, nitrification, leaching of nitrates, uptake and sequestration of non-acidic cations in oil palm biomass and harvested fruit bunches (Nelson *et al.*, 2014a). The burning of fallow vegetation and subsequent incorporation of ash material in food garden soils is expected to contribute to enrichment of bases. However, other soil processes such as addition and decomposition of crop biomass and loss of bases through leaching, crop uptake and runoff could have counteracted accretion of basic cations in food gardens.

More land use change is expected in the coming years to expand smallholder oil palm production largely due to socio-economic benefits associated with the crop. Unfortunately, much of the research on oil palm nutrition is directed towards rationalizing use of nutrients such as N, P, K, Mg and B (Comte *et al.*, 2012). There is not much information available on the extent of S deficiency in oil palm plantations except for report from Gerendás *et al.* (2011) in Indonesia. Sulfur status has been found to be severely deficient in several oil palm blocks based on leaf sample analysis. Deficiency of S leads to decreasing use efficiency of N fertilisers in oil palm which is not acceptable as fertilisation costs make up more than 60–65 % of the upkeep cost of plantations. Equally concerning was the fertility status of the food gardens within the oil palm blocks. Besides S, N and K were in deficient supply to the sweet potato crop in food gardens. With the increasing population of oil palm dependents and concomitant intensification of food gardening multi-nutrient deficiencies are emerging. From the results of the study, it appears that sustaining garden food production and oil palm productivity requires use of mineral fertilisers and cheap S sources. For managing S deficiency, mineral S fertilisers such as sulfate of ammonia or kieserite ($MgSO_4.H_2O$) could be used.

Further studies are required to evaluate improved soil organic matter management strategies and use of mineral S sources in the food gardens. Suggested strategies are avoiding burning of fallow vegetation, improved fallows, soil mulching with fallow biomass, besides, use of manures and S containing fertilisers. Possible organic matter management strategies may include improved fallows and mulching slashed fallow vegetation. Such strategies may help to improve S cycling in the soil-plant system, besides reducing S losses to atmosphere.

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