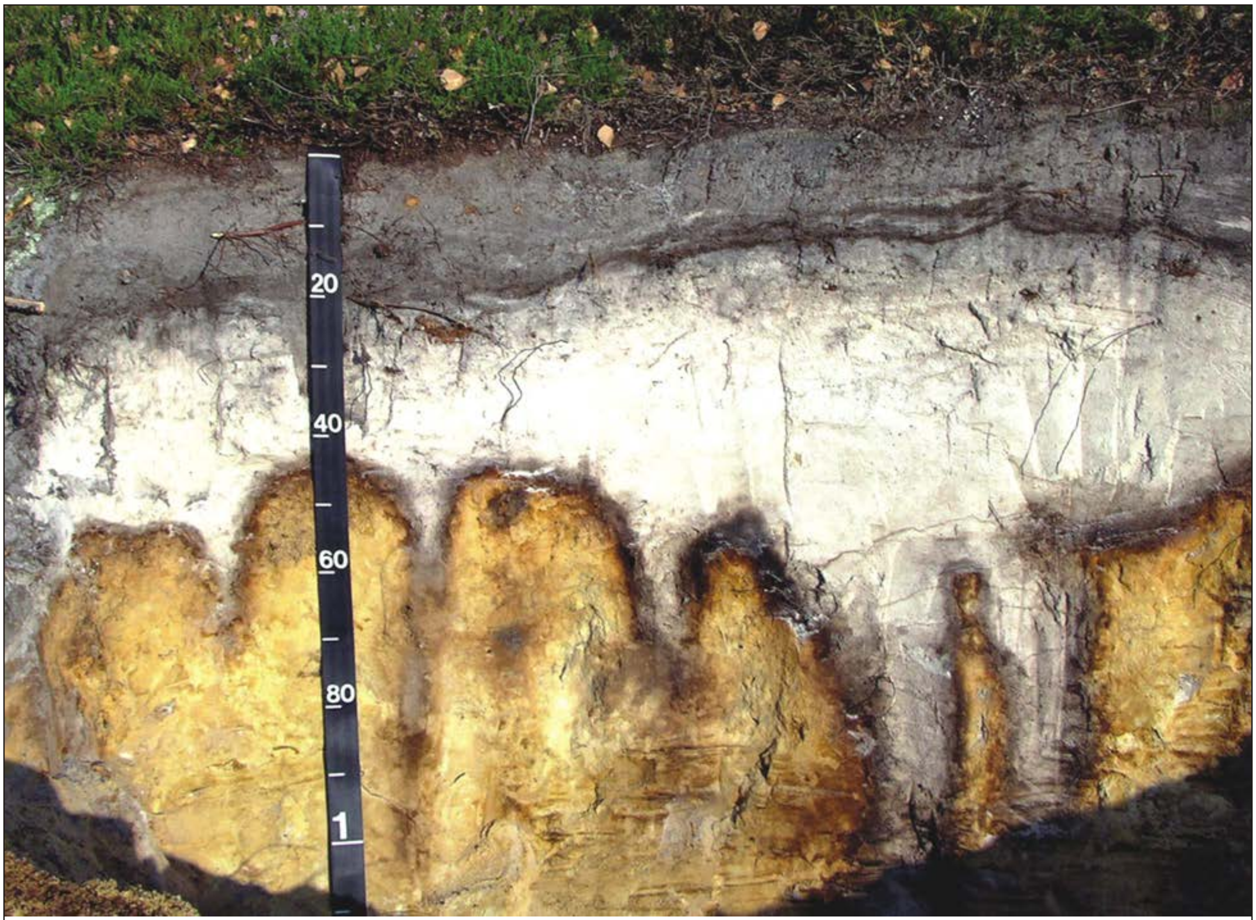

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Changes in Soil Organic Matter and Soil Aggregation of a Zambian Oxisol after Applying Lime

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Abstract: In this study we investigated factors that contribute to poor crop response to lime. Soil samples were collected from three depth increments (0-15, 15-30 and 30-45 cm) in trial plots with the following treatments: lime only, urea only, urea + lime, no lime no urea-cultivated and fallow no lime (control). The samples were analyzed for Soil Organic Matter (SOM), exchangeable cations (Ca, Mg and K) and soil aggregate stability. The highest SOM content (36.8 g kg^{-1}) was measured in the fallow plot and the least in the plot fertilized with urea. While exchangeable Ca increased in limed plots the level of exchangeable K decreased. The low SOM in fertilized plots was corroborated by the measured decrease in soil aggregate stability. Lime had a positive effect on soil aggregate size, but the best effect was obtained from the fallow plot. This study has shown that the effect of lime on acid soils is variable and probably soil specific. Therefore, in practice, soil amendment with lime has to be considered on a case by case basis.

Key words: Acid soils, lime, mean weight diameter, soil organic matter, Zambia

INTRODUCTION

Soil acidity poses a serious challenge to the crop production capacity of many soils in the tropics and subtropics (Giller, 2001). Experience in Zambia has shown that crop yields can be drastically depressed due to this phenomenon (Lungu and Chinene, 1993). In order to reduce the problems caused by soil acidity, there is convincing evidence that ground agricultural limestone (lime) is effective hence it is used widely and successfully (Yerokun, 2006; Bolan *et al*., 2003). Lime works by neutralizing acidity and complexing exchangeable aluminum which can be toxic to and limit the functioning and growth of plant roots (Ritchie, 1989). It raises soil pH to levels that are desirable for crop production such that the availability of most of the elements that are essential to plants is improved. In addition, lime promotes an optimum population of useful soil microorganisms that are essential to decompose soil organic matter (Haynes and Naidu, 1988). Lime has also been shown to be effective in attenuating heavy metals in contaminated soils (Adriano, 2001) and reducing their uptake by plants.

While agricultural lime is widely recognized for its many positive attributes when applied to soil, there are also some negative effects that may arise from the application of lime to soil (Bolan *et al*., 2003). For instance, because lime promotes soil organic matter decomposition, the increased mineralization of nitrogen, phosphorus and sulphur may lead to a higher potential for the loss of these elements through leaching and erosion (Borah *et al*., 2000; Neale *et al*., 1997; Marchner and Wilczynski, 1991). There is conflicting information about the effect of lime on soil structure. Chan and Heenan (1999) observed that lime increased the aggregate stability of soil while Roth (1991) and Roth and Pavan (1991) reported that lime negatively affected soil structural stability. In their study, Chan and Heenan (1999) also observed that lime induced soil organic carbon leaching. When considered therefore, while application of lime may improve soil structural stability from Ca-bridging, leaching losses of nutrients may also be enhanced.

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It has been suggested that several of the negative effects to soil as well as negative plant response associated with the use of lime are more likely to occur on tropical and subtropical soils (McLean, 1971). This is probably because when compared with temperate soils, they have a higher rate of leaching and weather faster from high soil temperatures and precipitation (Wilcke *et al*., 1999). Therefore, application of high rates of lime in the tropics, based upon information derived from temperate regions should be done with caution as it can be detrimental (McLean, 1971). Due consideration must be given to the differences in soils and the processes they undergo.

In recent times, there has been resurgence in the promotion and use of lime especially in the small-holder farm sector in Zambia. Aside from the government extension system, non-governmental organizations have been instrumental in setting up field demonstration plots, providing training, as well as input and logistics to support use of lime. These activities are based upon the positive results from earlier research work on the use of lime in Zambia. However, most of these studies which have been reviewed by Goma and Singh (1993) focused upon determining the response of various crops, particularly maize, groundnuts, soybeans and wheat to lime. There was little attention paid to the effects of lime on soil properties other than its effectiveness in reducing exchangeable aluminum concentrations and acidity. Given the potential for negative consequences, it is necessary to gain better understanding about the changes that occur in soils when lime is applied. The objective of this study was to determine the distribution and redistribution of soil organic matter as well as basic cations following cultivation of land and the application of lime and urea fertilizer. We hypothesized that lime would not effect downward leaching of organic matter and cations in this soil because of the constant nature of soil charge.

MATERIALS AND METHODS

Site Description

The study was carried out at the Golden Valley Agricultural Research Trust Station in Chisamba, about 65 km north of Lusaka, Zambia. The soil is classified as a Mutwale series, fine mixed Isohyperthermic Humic Eustrostox (Soil Survey Staff, 1999). It is a red sandy clay with 43% sand, 16% silt and 41% clay. In March 2003, soil samples were collected from a field study where phosphorus trial was initiated in November 2000. The original experiment was an evaluation of the agronomic effectiveness of Partially Acidulated Phosphate Rock (PAPR) and it is fully described by Lungu and Munyinda (2002). Briefly, 12 treatments that included applications of 60 or 120 kg PAPR ha^{-1}, 60 or 120 kg MAP ha^{-1}, 0 or 1.5 tons lime ha^{-1} and 60 or 120 kg N ha^{-1} (supplied as 130 or 260 kg urea: 46% N) were arranged in a randomized complete block design with three replications. The lime was broadcast on the soil surface one week before the first planting and urea was always applied as a top-dressing to the soil surface. The following treatments were selected for the current study: (I) Fallow (FL), (ii) No lime no urea (NT), (iii) 260 kg Urea ha^{-1} (UR), (iv) 1.5 ton Lime ha^{-1} (LM) and (v) 1.5 ton Lime + 260 kg Urea ha^{-1} (LU).

Soil Chemical Analysis

Soil samples were collected from the 0-15, 15-30 and 30-45 cm depths of each of the three replications of the selected treatments. The samples were air-dried and crushed to pass through a 2 mm sieve. Soil $pH_{(CaCl_2)}$ was < 4.6 for plots that had not received lime and > 5.9 for the limed plots. Soil organic matter was determined by the standard Walkley-Black potassium dichromate oxidation method (Nelson and Sommers, 1982). Exchangeable calcium, magnesium and potassium were extracted in neutral 1 N NH_4OAc and their concentrations were determined on an atomic absorption spectrophotometer (Lanyon and Heald, 1982). All samples were analyzed in duplicates.

Soil Physical Analysis

Undisturbed clods of soil were collected from the 0-20 cm layer and carefully packed to minimize the disturbance to soil aggregates. In order to dry sieve, 500 g of soil aggregates > 9.5 mm in diameter were weighed and placed on a nest of sieves with 4.75, 1.00, 0.50 and 0.30 mm openings. The nest was shaken for five minutes and the soil retained on each sieve was weighed and expressed as a percentage of the total soil weight. This procedure was repeated for wet sieving, except that the soil was moist. After shaking, the soil retained on each sieve was dried at 105°C, weighed and expressed as a percentage of total soil weight. The Mean Weight Diameter for the soil was then calculated using the equation:

$$X = \sum_{i=1}^{n} x_i . w_i \text{(Hillel, 1982)}$$

Statistical Analysis

Analysis of variance to determine the effect of treatment and soil depth on soil organic carbon, extractable base cations and mean weight diameter of soils was carried out on the data using MSTAT computer program (MSTATC, 1993). Treatment means were separated using Duncan's Multiple Range Test at the five percent level of significance.

RESULTS AND DISCUSSION

SOM

The Soil Organic Matter (SOM) contents detected in the plots were significantly different ($p<0.05$) among the five treatments, the three soil depths and their interaction (Table 1). The fallow plot (FL) had the highest mean SOM content of 36.8 g kg^{-1} (Table 2). This was probably as a result of accumulation of litter from continuous residue addition and an absence of soil disturbance for an extended period. Without activities that invert the soil and expose SOM in this plot, it is very likely that there would be an appreciable degree of physical and chemical protection of SOM by clays. When

Table 1: Analysis of variance of the effect of applying lime and urea on soil organic matter (SOM), exchangeable potassium, calcium and magnesium concentrations and mean weight diameter of a Mutwale series soil

		SOM		K		Ca		Mg		MWD (dry)		MWD (wet)	
Source	df	F	Prob.	F	Prob.	F	Prob.	F	Prob.	F	Prob.	F	Prob.
Replication	2	0.87	ns	1.00	0.33	1.07	0.30	2.91	0.110	0.35	0.710	0.64	0.560
Treatment (T)	4	397.70	0.001	171.00	0.001	4.93	0.01	125.80	0.001	54.86	0.001	72.85	0.001
Depth (D)	2	854.73	0.001	1.00	0.39	13.62	0.001	87.62	0.001				
T×D	8	45.86	0.001	103.50	0.001	4.07	0.01	76.68	0.001				

Table 2: Bulk soil average soil organic matter content, cations concentrations and mean weight diameters following cultivation and application of lime and urea to a Mutwale series soil

					MWD[‡]	
	SOM[†]	K	Ca	Mg	Dry	Wet
Treatments	(g kg^{-1})		(cmol kg^{-1})		(mm)	
FL[§]	36.8a[¶]	0.15c	0.38b	0.15b	2.6a	2.50a
NT	32.3b	0.15c	0.38b	0.09d	1.9c	1.80c
LM	30.7c	0.17a	0.48a	0.15b	2.3b	2.10b
UR	29.0d	0.17a	0.36b	0.18a	1.6d	1.40d
LU	28.3e	0.16b	0.36b	0.12c	1.9c	1.70c
CV (%)	1.69	3.06	13.81	5.37	4.62	4.53[†]

[†]SOM = Soil organic matter, [‡]MWD = Mean Weight Diameter, [§]FL = Fallow, NT = No lime no urea, UR = Urea only, LM = Lime only, LU = Lime plus, urea, [¶]All means with the same letter within a column are not significantly different at the 5% probability level using the Duncan Multiple Range Test

lime or urea was applied to the soil, SOM content was observed to decrease (Table 2). Consequently, SOM in the lime only (LM) plot was 17% less than in the FL plot while that in the urea only (UR) plot was 21% less than what was found in the FL plot. The decline in SOM was more when urea alone was applied than when lime alone was applied. However, it is clear that the effect of combining lime and urea in a plot was not additive since SOM content in the lime plus urea (LU) plot was only 23% less than in the FL plot.

Soil organic matter content in the untreated-no lime no urea plot (NT) which had only been subjected to physical disturbance from cultivation was 32.3 g kg^{-1} (Table 2). This value exceeded SOM content in the LM plot by 5%, the UR plot by 11% and the LU plot by 14%. Conversely, SOM content in the NT plot was 12% less than in the FL plot. It would, therefore, appear that physical disturbance of the soil by cultivation induced a slower rate of SOM decomposition than found in the plots that received chemical amendments. The reductions in SOM that were observed with the chemical treatments may be explained by the accompanying rise in soil pH and increase in soil microbial activity which occurs following liming (Haynes and Swift, 1988). This will cause SOM to decompose at a faster rate. Reports of loss of SOM content following application of lime has also been reported by Chan and Heenan (1999) in New Zealand and Baldock *et al*. (1994) in Australia. Variable charge or more weathered soils appear to be more susceptible to this phenomenon. Additions of nitrogen to the soil, such as in urea result in a narrowing of the soil C:N ratio which similarly increases microbial population and activity, creating a more conducive environment for faster decomposition of SOM (Giller, 2001).

As the depth of soil sampling increased, a significant ($p<0.05$) decrease in SOM contents was observed for almost all the treatments (Table 1 and 3). Generally, this would be expected since biomass that is returned to the soil as residue is basically mixed into the surface soil. Present observation is in contrast to that by Chan and Heenan (1999) where the lime induced soil organic carbon leaching in a variable charge soil. Temminghoff (1998) suggested that while the rise in pH from liming may enhance solubilization of SOM, the Ca in lime is also effective in reducing the amount of negative charges on Dissolved Organic Carbon (DOC). This will lead to coagulation of DOC, which conceivably may account for the absence of noticeable leaching of SOM following liming in our study.

Exchangeable Cations

Potassium

The soil cation concentrations were generally low. In the case of potassium (K), McLean (1971) suggested that tropical soils have a low K release tendency. Bulk soil exchangeable K concentrations were more than 6% higher in the LM and UR plots than in the other treatment plots (Table 2). It is likely that lime-derived calcium (Ca) entered into competition with K for cation exchange sites, causing K to be displaced into the soil solution more easily. Galindo and Bingham (1977) demonstrated this replacement effect in a batch experiment where they observed a decrease in K sorption by soil hence more K displaced into soil solution following addition of increasing Ca concentration to the soil. In our case, lime would cause this increase in soil solution Ca concentration. The increase in extractable K observed in the UR plot was also probably as a result of urea derived NH_4^+ ions entering into competition with K. Whereas K and NH_4^+ ions have similar non-hydrated and hydrated ion diameters, a higher concentration of NH_4^+ ions would displace K from the clay into solution (Tan, 1998). When the soil depths are considered, K concentrations increased with depth in the plots that received lime, LM and LU (Table 3). The reverse was true for the plots that did not receive lime application. Potassium concentration either decreased with depth or remained stable. This observation for the limed plots strengthens earlier suggestion that K was being displaced from exchange sites by the lime derived Ca and probably also leached downwards in the soil profile. The fact that K concentrations decreased with depth in the FL plot (Table 3) which was only subject to growth of plants on it, suggests that

Table 3: Soil organic matter, potassium, calcium and magnesium distribution in the soil profile following application of lime and urea to a Mutwale series soil

Treatments	Depth (cm)	SOM[†] (g kg^{-1})	K	Ca	Mg
			------------------------ (cmol kg^{-1}) ------------------------		
FL[‡]	0-15	42.5	0.17	0.38	0.17
	15-30	38	0.14	0.31	0.08
	30-45	30	0.14	0.45	0.18
NT	0-15	36	0.15	0.32	0.06
	15-30	34	0.15	0.35	0.14
	30-45	27	0.15	0.46	0.08
LM	0-15	35	0.15	0.45	0.15
	15-30	31	0.17	0.46	0.13
	30-45	26	0.18	0.50	0.18
UR	0-15	36	0.18	0.43	0.16
	15-30	26	0.17	0.30	0.17
	30-45	25	0.17	0.34	0.22
LU	0-15	30	0.15	0.44	0.19
	15-30	29	0.17	0.18	0.07
	30-45	26	0.16	0.48	0.09

[†]SOC = Soil organic matter, [‡]FL = Fallow, NT = No lime no urea, UR = Urea only, LM = Lime only, LU = Lime plus urea

removal of K by plant roots from lower soil profile may play a considerable role in K distribution and re-distribution in this undisturbed soil. A uniform K concentration in the NT plot may have been the result of mixing of layers from cultivation, without chemical amendments that compete with K.

Calcium and Magnesium

Calcium concentration in bulk soil was only affected by the application of lime and this resulted in a 25% higher exchangeable Ca concentration in the LM plot than the other treatment plots (Table 2). Generally, Ca concentrations in the 15-30 cm layer of treatments were lower than in the 0-15 cm layer and then increased again in the 30-45 cm layer (Table 2). This may suggest some degree of natural leaching of Ca, probably with water flux. Whereas magnesium (Mg) was supplied in the dolomite lime, the pattern of influence of treatment on Mg concentrations was not obvious (Table 2 and 3). When lime is added to soils, the soil solution concentrations of Ca and Mg change from the input of these ions. However, a concurrent change in pH of the soil also has effect on the extent and nature of the cation exchange complex. All these contribute to the possibility of shifting the equilibrium between solution and exchangeable cations (Bolan *et al*., 2003). Additionally, the interactions which take place between organic matter and Ca and Mg can be rather complex and situation specific and can confound explanation of some of the observations made in this study.

Mean Weight Diameter

Soil mean weight diameter ranged from 1.6 to 2.6 mm (dry) and 1.4 to 2.5 mm (wet) and the patterns observed for dry and wet sieved MWD of soil aggregates were similar (Table 2). The highest values were observed in the fallow plot. As seen from the lower MWD values for the NT treatment (1.9 and 1.8 mm) without addition of chemical amendments, cultivation alone was adequate to induce aggregate disintegration. Soil aggregate sizes in the plots that received lime, LM and urea, UR were significantly ($p<0.05$) lower than in the FL plot. However, the positive effect of lime on soil structure is seen in the 21% (dry) and 17% (wet) larger aggregate sizes in the LM plot than in the NT plot. It would appear that Ca contributed by lime acted as a bridge to bind the soil particles together. Chan and Heenan (1998) observed that soil aggregate formation and saturated hydraulic conductivity were improved by Ca in the liming material. This effect was achieved by the influence of Ca on dispersion and flocculation of the soil. Calcium reduces the thickness of the diffuse-double layer, causing soil particles to become attracted to one another with increase in flocculation (Rengasamy, 1983).

Additionally, when lime promotes an increase in microbial biomass and enzyme activity (Haynes and Swift, 1988), this leads to production of polysaccharides that can act as binding agents with positive influence on soil aggregation.

The plot treated with urea, UR consistently had the lowest MWD of 1.6 (dry) and 1.4 mm (wet) (Table 2). As was observed with SOM levels, it is likely that the N supplied to soil in urea contributed to a lower C:N ratio, increased microbial population and activity and accelerated the loss of SOM and organic binding agents. Wagner *et al.* (2007) demonstrated that incorporating barley straw to build up soil organic matter in Australian soil enhanced soil aggregation. Since both lime and urea increase microbial population, the better MWD with lime suggests a stronger contribution of Ca to aggregate stability in this instance. The process of urea transformation leads to the release of protons into and acidification of the soil. This can cause acid decomposition of aggregates hence poorer soil structure. The similarities in the general pattern of MWD between dry and wet sieved soil suggests that the Ca or urea were the principal agents that influenced differences in soil aggregation among the treatments.

CONCLUSION

This study has shown that while lime may raise the pH of soil and neutralize exchangeable aluminum, it may also have some negative effects on soil properties. Lime did not induce leaching of soil organic matter but accelerated the rate of decomposition. This may be good for release of nutrients into the soil but detrimental in acid soils where farmers are encouraged to raise soil organic matter levels. Lime displaced K from the soil exchange complex and this led to its leaching into lower horizons. Calcium was apparently effective in the bridging of soil aggregates and this role could be important in the structural stability of many soils. These conflicting results from application of lime may in part explain why high lime rates do not work in many tropical region soils.

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