Impact of Land-use Systems on some Physical and Chemical Soil Properties of an Oxisol in the Humid Forest Zone of Southern Cameroon

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Summary

A field study was carried out in the village Ngoungoumou in the humid forest zone of Cameroon to assess changes in particle size distribution and soil chemical properties in relation to different land-use systems. These strongly acid soils are mainly composed of clay and sand, and are generally devoid of crop nutrients at the benefit of exchangeable Al occupying the nearly entire exchange complex. The major portion of the nutrients is stored in the top-soil, together with the organic matter. Land-use systems significantly affected the clay, the silt and the sand fractions. Sand and silt decreased with the soil depth whereas clay increased with it. Soil pH, total N, organic carbon, available P, exchangeable Ca, exchangeable Al, sum of bases, ECEC and Al saturation significantly differed with the land-use systems. Al saturation increased with soil depth, and the top-soils presented acidity problems while the sub-soils exhibited Al toxicity. Chromolaena odorata *fallows presented relative higher soil fertility, secondary forests and cocoa plantations the lower. Utilization of harvest residues, wood ash or lime; Ca, N, P, K and Mg fertilizations according to crop requirement; acid-tolerant crops and N fixing trees for acid soils appear to be the most appropriate soil management options.*

Résumé

Impact des systèmes d'utilisation des terres sur quelques propriétés physiques et chimiques d'un Oxisol dans la zone forestière humide du Sud Cameroun

Une étude a été effectuée dans le village Ngoungoumou en zone de forêt humide du Sud Cameroun en vue d'évaluer les fluctuations de la texture et des propriétés chimiques du sol par rapport aux différentes utilisations des terres. Ces sols très acides sont principalement composés d'argile, et sont généralement dépourvus d'éléments nutritifs au profit de l'Al échangeable occupant presque entièrement le complexe d'échange. La majeure portion d'éléments nutritifs est stockée dans la couche supérieure avec la matière organique. Les systèmes d'utilisation des terres ont affecté significativement les fractions argileuse, limoneuse et sableuse. Le pH du sol, l'azote total, le carbone organique, le P assimilable, le Ca échangeable, l'Al échangeable, la somme des bases, l'ECEC et la saturation d'Al varient significativement suivant les types d'utilisation des terres. L' azote total et la saturation d'Al augmentent avec la profondeur du sol. Les jachères de Chromolaena odorata *montrent une fertilité élevée alors que les forêts secondaires et les* cacaoyères *présentent une fertilité faible. L'utilisation des résidus de récolte, des cendres de bois, le chaulage et les fertilisations calcique, azotée, phosphatée, potassique et magnésique, la mise en plantation de cultures et de légumineuses acido-tolérantes paraissent être les alternatives les plus appropriées de gestion des sols.*

Introduction

Lal (16) and Shepherd *et al.* (30) experienced that land use in tropical ecosystems could cause significant modifications in soil properties. Schipper and Sparling (29), and Birang *et al.* (2) added that those modifications were biologically and chemically more rapid than physically. Forest ecosystems are important both ecologically and economically. It is arguable that the most fundamental dynamic of the forest ecosystem is the forest soil. The acidity of forest soils can alter the chemistry, biology, and hydraulics of the soil, and thus, alter the soil formation characteristics and the soil composition. In consequence, that in the fragile tropical forest ecosystems, the acidification of soils demands a great deal of research and attention. In the humid forest zone of Cameroon, slash-and-burn is commonly practiced to settle perennial or annual crops. Shifting cultivation, with one to two years of cropping followed by fallow periods, is widespread. Research of impacts on the soil is important to determine how soil fertility can be maintained and the land-use systems improved. Shepherd *et al.* (30) observed no change in particle size distribution and significant modifications in chemical properties in the top-soil that affects agricultural productivity. In this study, the effects of land-use systems are evaluated on the following soil properties: particle size distribution (sand, clay, silt), pH, organic carbon, total nitrogen, available P, exchangeable bases (Ca, Mg, K), exchangeable Al, ECEC, base saturation and Al saturation in soils of secondary and young forests, cocoa plantations, *Chromolaena odorata* fallows and cropped fields of Ngoungoumou village near Ebolowa in Cameroon.

Material and methods

Location

The geographical references of Ngoungoumou village are 12° 01' E, 3° 18' N and its elevation is about 585 meters above the sea level in the forest zone of Cameroon (Figure 1). Annual rainfall in the area is bimodal. Rains start in mid-March and end in mid-June, followed by a short dry season of 7 to 8 weeks, then recommence in mid-September and stop in mid-December. The climate is humid tropical, with mean annual rainfall of 1350-1900 mm and air temperature of 22-26 °C. The natural vegetation is a dense humid semi-deciduous tropical forest. Most of the upland soils belong to the group of Kandiudox (35).

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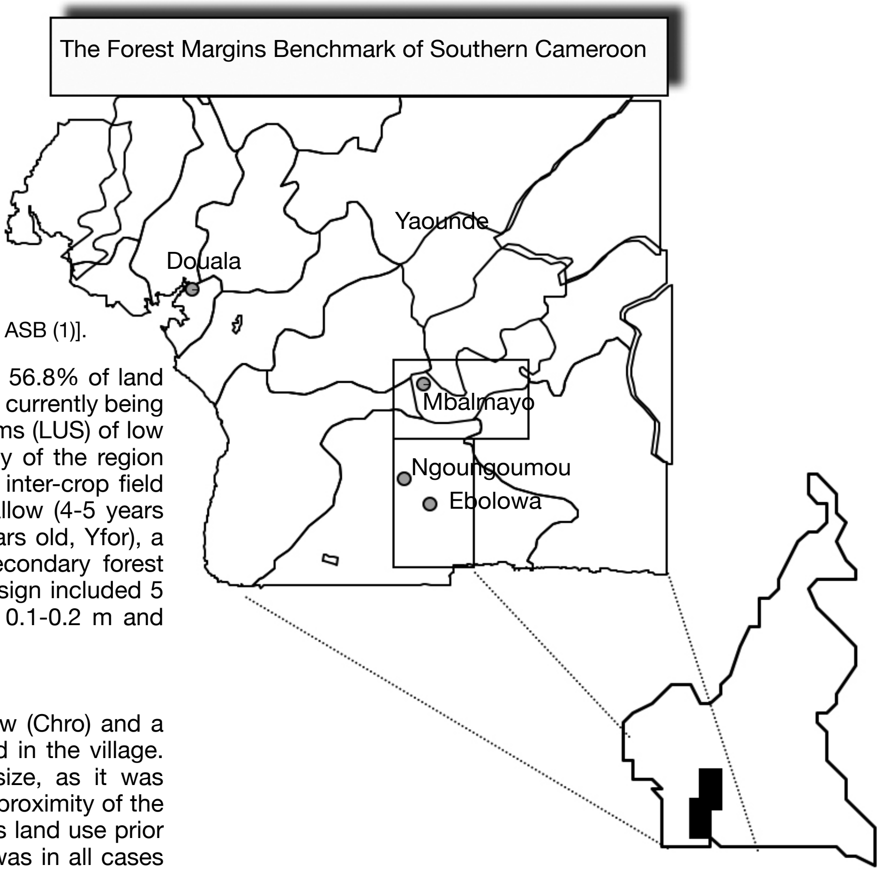

Figure 1: Location of the study site [adapted from ASB (1)].

According to Nolte *et al.* (23), this area has 56.8% of land under forest, 10.2% under fallow and 12.6% currently being cropped. The 5 commonest land-use systems (LUS) of low level of deforestation and land-use intensity of the region are: a groundnut / maize / cassava annual inter-crop field (Crop), *Chromolaena odorata* dominated fallow (4-5 years old, Chro), a young forest fallow (12-15 years old, Yfor), a shaded cocoa plantation (Coco) and a secondary forest (> 30 years old, Sfor). The experimental design included 5 land-use systems, 3 soil depths (0-0.1 m, 0.1-0.2 m and 0.2-0.3 m) and 5 replicates.

Experimental set-up

A 4-5 years old *Chromolaena odorata* fallow (Chro) and a 10-12 years old forest (Yfor) were identified in the village. The site was selected on the basis of: size, as it was required to be at least 100 m x 25 m large; proximity of the two vegetation types; and, that the previous land use prior to vegetation succession to Chro or Yfor, was in all cases a mixed food crop field dominated by groundnut, maize and cassava. The site was divided into 6 plots, 15 m x 15 m, located in the centre of the site and thus leaving border up to 5 m with the bordering vegetation. Three plots were cleared and burned and 3 served as undisturbed controls. In February 2000, the Chro plot and the under-storey of the Yfor were slashed. In the Yfor plot, all trees were manually felled. The biomass was left to dry and burned by the end of March 2000. In both fallow types, unburned materials were piled and burned again. The 3 cropped and the 3 undisturbed plots served as replicates.

An intercrop of groundnut (*Arachis hypogea* L.) local cultivar, maize (*Zea mays* L.) cultivar CMS 8704 and cassava (*Manihot esculenta* Crantz) cultivar 8017 was planted in both fallow types. First, groundnuts were seeded at approximately 20 seeds.m^{-1}, by tilling the grains into the soil with hand hoes. Cassava was planted at 1.5 m x 1.5 m inter- and intra-row distance. Two, approximately 0.3 m long, cassava sticks were planted in each hole. Two pockets of two maize seeds were planted between cassava pockets at 0.5 m distance between cassava pockets, yet only in one direction of the lines. Seedlings were in April 2000 and 2001.

Soil sampling, physical and chemical analyses

Between May and August 1999, prior to establishing the cropped plots, five monoliths of 0.5 m x 0.5 m x 0.3 m (L x W x D) were dug out along a 100 m transect in each fallow. Soil samples were taken from these monoliths at three different depths (0-0.1 m, 0.1-0.2 m and 0.2-0.3 m) for physical and chemical analysis. Bulk soil samples were horizontally collected, air-dried, ground to pass a 2-mm mesh sieve and used for determining soil textural classes and chemical characteristics.

In 2001, soil was sampled at 0-0.1 m, 0.1-0.2 m and 0.2-0.3 m depths at groundnut and maize harvest in July. All the samples were oven dried at 65 °C, the ground to pass through a 0.5 mm mesh size sieve and analyzed for pH, total N, organic C, available and exchangeable Ca, Mg, K and Al.

Soil particle size was determined by the pipet method (10). Soil pH was determined in a water suspension at a 2:5 soil/ water ratio. Exchangeable Ca^{2+}, Mg^{2+}, K^{+}, Al^{3+} and available P were extracted by the Mehlich-3 procedure (19). Cations were determined by atomic absorption spectrophotometry and P by the Malachite green colorimetric procedure (21). Organic C was determined by chromic acid digestion and spectrophotometry (11). Total N was determined using the Kjeldahl method for digestion and ammoniumelectrode determination (3, 4).

Statistical and numerical analyses

Analyses of variance were conducted using the General Linear Model (GLM) procedure of SAS. Statistical comparisons of land-use systems were performed by analysis of variance. The data for the various soil depths were grossly analyzed. When an F-test proved significant at $p< 0.05$, the means were grouped after the Student-Newman-Keuls Test.

Results and discussion

Effect on soil particle size distribution

The soils are mainly composed of sand and clay, clay being the most representative fraction. Silt represents 22.34 per cent in the top 0-0.1 m layer, 19.67 per cent in the 0.1-0.2 m layer and 12.59 per cent in the 0.2-0.3 m layer. The top-soil (0-0.1 m) features as a clay loam and the sub-soil as a clay. This derives from the dissolution and leaching of silica due to high rainfall.

Land-use systems significantly affected the sand, the clay and the silt fractions of the soils (Figure 2). The sand and silt percentages decreased with the depth whereas the clay percentage increased with it, which was a sign of clay translocation. Clay accumulation in the sub-soil could result in reduced porosity, increased water retention and reduced drainage. But Voundi Nkana and Tonye (38) did not find that land-use systems affect the silt fraction distribution may be because their soils had less silt (11.6 per cent) compared to

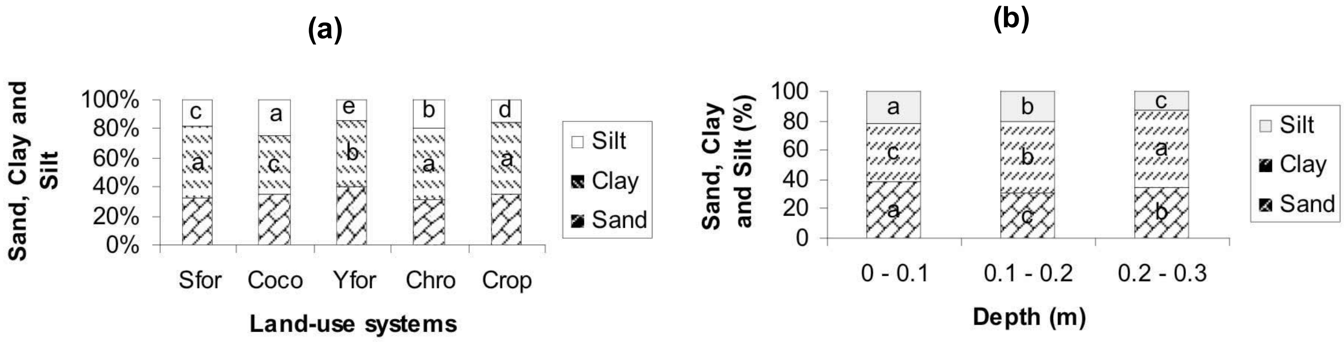

Figure 2: (a) Effect of land-use systems on soil particle size distribution (b) Soil particle size distribution in relation to the depth.

the present ones (21 per cent) within the top 0-0.2 m layer. Kauffmann *et al.* (15) and Voundi Nkana and Tonye (38) found similarly that continuous cropping and intensive land use affected the particle size distribution and that these changes related to cultivation time. On the contrary, Shepherd *et al.* (30) observed no effect of land-use systems on soil particle size distribution. The closeness or differences of results might be due to the similarities or differences in ecosystems and climates of the places of the experiments. Nevertheless, as the overall soil texture must take into account both soil organic carbon and Ca contents (7), soils under *Chromolaena odorata* fallows had the highest Ca contents and the rest of land uses the lowest. Soils under secondary forests had the highest organic carbon contents and *Chromolaena odorata* fallows the lowest. All the land-use systems had a clay texture, except cocoa plantations that had a clay loam texture (Figure 2a). All this let presume that *Chromolaena odorata* fallows had the highest fertility and secondary forests the lowest. That statement will have to be confirmed or denied by the interpretations of soil chemical properties.

Effect on soil chemical properties

All the measured soil chemical properties varied under the influence of the land-use systems (Table 1, Figures 3). Soil pH, total nitrogen, Organic carbon, available P, exchangeable Ca, exchangeable Al, base saturation, Al saturation and ECEC were significantly affected by the land-use systems.

Table 1
Effects of land-use systems on chemical properties of the soil

LUS	pH_{H2O} (1:2.5)	Total N (%)	Org. C (%)	LogavP* mg. kg^{-1}	Ca	Mg	K	Al	ECEC
					cmol. kg^{-1}				
Sfor	4.13c	0.17a	2.24a	0.98a	0.35b	0.27a	0.09a	4.39a	5.10a
Coco	4.30b	0.10b	1.35c	0.65b	0.32b	0.24a	0.07a	3.53b	4.16b
Yfor	4.59a	0.12b	1.72b	0.75ba	0.82b	0.50a	0.07a	1.90d	3.29c
Chro	4.75a	0.11b	1.48cb	0.47b	1.42a	0.43a	0.10a	2.70c	4.66ba
Crop	4.75a	0.10b	1.41c	0.74ba	0.75b	0.32a	0.08a	1.96d	3.12c
P	<0.0001	<0.0001	<0.0001	=0.0008	= 0.0006			< 0.0001	< 0.0001
R^2 (%)	85	88	87	89	71			91	79
C.V. (%)	4.17	21.26	19.63	41.88	97.80			17.43	16.70
√MSE	0.19	0.03	0.32	0.30	0.70			0.51	0.68
Mean	4.50	0.12	1.64	0.72	0.72			2.94	4.09

* LogavP= Log available P
LUS= Land-use systems.

Table 2
Soil chemical properties changes in relation to the depth

Depth(m)	pH_{H2O} (1:2.5)	Total N (%)	Org. C (%)	LogavP mg.kg^{-1}	Ca	Al	ECEC
					cmol.kg^{-1}		
0 – 0.1	4.45b	0.19a	2.52a	1.77a	1.60a	2.26c	4.62a
0.1 –0.2	4.33c	0.10b	1.29b	0.29b	0.25b	3.89a	4.42a
0.2 –0.3	4.72a	0.08c	1.16b	0.15b	0.35b	2.64b	3.26b
P	<0.0001	<0.0001	<0.0001	< 0.0001	<0.0001	<0.0001	<0.0001

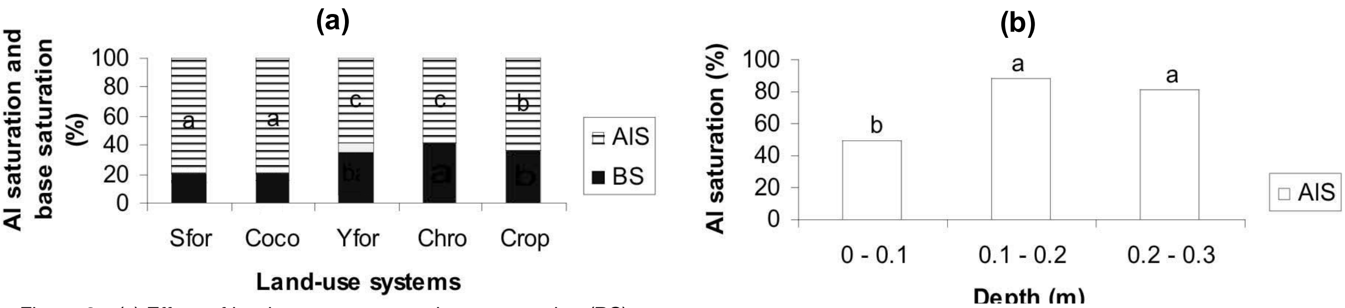

Figure 3: (a) Effect of land-use systems on base saturation (BS) and Al saturation (AlS) (b) Soil Al saturation changes in relation to the depth.

Soil pH and nutrients were low (Table 1). Due to the strong acidity (pH< 5.5), these soils contained Al in the exchangeable form. The very low ECECs reminded that the adsorption capacity of these soils was humus-dependent. Menzies and Gillman (20) and Voundi Nkana *et al.* (36) justified this low and variable character of the CEC within the Cameroon humid forest zone by the domination of low –activity components such as kaolinite, Fe and Al (hydr-) oxides in these soils. That resulted from the higher degree of weathering of rock constituent minerals. In such soils, a large part of the plant nutrients and about 90 per cent of the capacity of the soil nutrient retention depends on soil organic matter (15). Buol *et al.* (5) noted that soils with ECEC of 4 me/100g or less had limited ability to retain nutrient cations. The Al saturation increases with the soil depth (Figure 3b) from 49 per cent in the top-soil up to 81-88 per cent in the sub-soil (Table 2). Sanchez and Couto (27) defined two important thresholds values: soils with 10-60 per cent Al saturation present acidity problems while soils with more than 60 per cent Al saturation exhibit Al toxicity. Thus acidity problems will occur in the top-soil and Al toxicity problems in the sub-soil.

Statistically the three depths significantly differ for most soil properties except for Mg and K. The relative richness of the top 0-0.1 m layer (Table 2) could be attributed to the regular restitution of N, P and basic cations at the soil surface via decomposition or burning of plant residues or biomass (6). The limited amount of exchangeable Al in the top-soil could be due to complexation with organic matter because it is in that layer where this latter concentrated.

In general, soils of *Chromolaena odorata* fallows presented a higher fertility level (higher soil pH, higher Ca content and lower Al saturation) compared to those of the other land-use systems (Table 1, Figure 3a). Soils under secondary forests and cocoa plantations showed a lower soil fertility level.

Although in another soil types and climate, and with different land-use systems, Schipper and Sparling (29) and Shepherd *et al.* (30) obtained similar results for the chemical status among land-use systems. According to those authors, soil chemical status was increased in non-woodland systems, due to management. The highest soil fertility status in *Chromolaena odorata* fallows could be thus due to the fact it is herbaceous, covers well the soil-surface and does not immobilize plant nutrients for a long period in the standing biomass leading to a shortening of the nutrient cycling. In addition, these fallows might have especially taken advantage of the residual effect of the wood ash from the slash-and-burn practice.

In cropped fields, the ash deposited by the slash-and-burn practice releases alkaline cations (Ca, Mg and K) and P, causing high pH, available P and low exchangeable Al values (6, 13). The lowest content of organic carbon in soils under cropped fields is due to the rapid decomposition and mineralization of organic matter subsequent to clear cutting of the forest and burning (24) because of low temperature and low pH. Indeed, high temperature and high pH stimulate biological activity. Therefore, decomposition rates of organic matter increases with increasing temperatures and pH. The reverse situation occurs in the case of secondary forests.

The lowest soil fertility status in secondary forests and cocoa plantations is due to natural acidity conditions in the soil (6). Moreover, Erisman and Heij (8) found that natural and anthropogenic atmospheric acidifications take place regardless of the type of land use. According to them, apart from rarely serious direct damage by NH_3 and SO_2 on plant leaves, atmospheric acidification on arable land is of little concern in the Netherlands. Firstly, most agricultural land is regularly limed or made so to undo the effects of natural acidification and of crop removal. Secondly, forest soils are usually poorer (i.e. lower in bases and in weatherable minerals) than most agricultural soils, and are therefore more sensitive to acidification by strong mineral acids. Thirdly, dry deposition is generally higher on trees than on lower vegetations, increasing the acid deposition on forests relative to that on agricultural land. Deposition on forests is increased most strongly along forest edges. Acid forest soils often develop high levels of soluble aluminum. In fact, the more acidified a soil is, the more aluminum rich clay particles will release Al into solution (31). This can be seen from field research as demonstrated by Mulder *et al.* (22).

Differentiation factors

Under secondary forests and cocoa plantations, erosion is minimal and the particle size distribution is dominated by the clay fraction in the top and sub-soil (Figure 2). Soil fertility then depends on the organic matter supply by the natural vegetation and the nutrient cycling (13). In cropped fields, exposure of the soil surface to heavy rains brings about erosion, rapid decomposition and mineralization of soil organic matter, and intense leaching of nutrients. Important changes could therefore occur in base and Al saturation, and in soil nutrient levels (Table 1, Figure 3). In cropped fields, a significant benefit of slash and burn is the rapid release of nutrients from the ash to the soil (12, 34). Burning and plowing lead to the destruction and rapid decomposition of soil organic matter and reduce the contribution of organic and microbial processes to nutrient cycling (13). However, the fertility status depends on the inevitable loss of soil nutrients in crop harvest and additional losses by leaching and runoff.

Consequences for agricultural development

Soil acidity and aluminum toxicity constrain agricultural production in several ways. Farmers are limited to planting crop species or cultivars that tolerate such conditions. Many acid soils "fix" or hold phosphorus, making it unavailable for plant growth. Soil acidity can also be a barrier to root development, limiting a plant ability to reach moisture in the sub-soil. In the humid tropics, soil acidity and associated problems often lead to land abandonment and the perpetuation of slash-and-burn agriculture (33). These conditions are inherent to the nature of the soils of the rainforest zone.

Recommendations

Improving and maintaining soil productivity include erosion control, liming and fertilizer application. Residues from harvests must be used to cover the soil surface in order to minimize the effects of erosion especially in cropped fields. For nutrients that persist in the soil such as P, Mg and K, commercial fertilizers can compensate for nutrients taken up by plants or lost by runoff and leaching. For mobile nutrients like N, because uptake, runoff and/or leaching can be immediate, adding commercial fertilizers is not an option but a must and the application must be split.

Between 3.14 t and 7.24 t $CaCO_3.ha^{-1}$ (or 1.76 t to 5.34 t CaO ha^{-1}) must be applied to increase the soil pH and eliminate Al toxicity (14). Phosphorus additions must take into account both the adsorption capacity and P requirements of the soil (20). Phosphorus requirements in soils under different land-use systems, as determined by using the relationship established by Menzies and Gillman (20) for various humid forest zone top-soils of Cameroon, ranged from 119 to 175 $kg.ha^{-1}$ (Table 3).

Basic cations must be applied in proportion to achieve an ideal soil complex. According to Liebhardt (18), the ideal is to have the exchange complex saturated with 65 per cent Ca, 10 per cent Mg and 5 per cent K. But fluctuations of between 65 and 85 per cent Ca, 6 and 12 per cent Mg and, 2 and 5 per cent K do not affect the production capacity of the soil. Calculations showed that in all the land-use systems, none of the plant nutrients fulfils the ideal condition of

Table 3
Lime, Ca, N, P, Mg and K requirements

Land-use systems	Lime (t ha^{-1})		Ca	N	P	Mg	K
	$CaCO_3$	CaO	(t ha^{-1})		(kg ha^{-1})		
Sfor	7.24	4.06	2.97	0.83	175	144	161
Coco	5.82	3.26	2.38	1.00	137	106	135
Yfor	3.14	1.76	1.32	0.95	147	103	92
Chro	4.46	2.50	1.61	0.98	119	22	130
Crop	3.24	5.34	1.28	1.00	146	5	74

saturating the exchange complex stated above. So Ca, Mg and K cations have been ideally made adsorbed. According to the guidelines advocated by Landon (17), N is rated low in all these land-use systems and has been brought up to the medium level.

Secondary forests on strongly acid and leached soils depend on internal cycling to meet their mineral requirements (13) and do not need nutrient management. Recommended rates of nutrient application are listed in table 2.

Management options

Farmers finding lime and mineral fertilizers expensive look forward to cheaper alternatives. Agroforestry seems to be the most appropriate. The use of acid-tolerant species or cultivars is the first step for low-input soil management (25, 26). In addition, agroforestry is considered particularly applicable to marginal soils with severe physical, chemical or drought constraints (28). On acid soils of the tropics, the fundamental challenge is to recycle the limited nutrients available in soil-plant systems (32). Planting nitrogen fixing trees and crops in agroforestry system is one low-input technology that helps maintain levels of nitrogen, a key nutrient for plant growth.

An even cheap alternative for the farmers of Ngoungoumou is the use of wood ash, which is widely available and considered as waste by the wood industries. Since the government stopped subsidizing the use of commercial fertilizers and amendments, the use of wood ash, is a justified option, as no farmers have no access to financial credit. Ash is a good source of Ca, K, P and Mg (9). Its application in tropical acid soils can help increasing soil pH and neutralizing Al toxicity and at the same time it could supply P and K (37, 38).

Conclusion

The strongly acid soils of Ngoungoumou area are mainly composed of sand and clay. They are poor in organic carbon, total nitrogen and ECEC. The soil nutrients are mainly stored in the top-soil, together with the organic matter. Land-use systems significantly affect the clay, silt and sand fractions. High proportions of clay are found in soils of secondary forests, *Chromolaena odorata* fallows and less in soils under cocoa plantations. Soil pH, exchangeable Al, organic carbon, available P, base and Al saturations, exchangeable Ca and ECEC significantly changed with the land-use systems. Soils of *Chromolaena odorata* fallows presented a higher fertility level than those under secondary forests and cocoa plantations. For agricultural development, utilization of harvest residues, wood ash or liming; Ca, N, P, K and Mg fertilizations according to crop requirement; acid-tolerant crops and N fixing trees for acid soils appeared to be the most important management options.

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